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GUDRUN ALM CARLSSON

DOSIMETRY AT INTERFACES
THEORETICAL ANALYSIS AND MEASUREMENTS BY
MEANS OF THERMOLUMINESCENT
LiF

STOCKHOLM 1973

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DOSIMETRY AT INTERFACES

THEORETICAL ANALYSIS AND MEASUREMENTS BY
MEANS OF THERMOLUMINESCENT LiF AT PLANE
INTERFACES BETWEEN A LOW Z-MATERIAL AND
Al, Cu, Sn OR Pb IRRADIATED WITH 100 TO
200 KV ROENTGEN RADIATION

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GUDRUN ALM CARLSSON

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ACTA RADIOLOGICA SUPPLEMENTUM 332

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DOSIMETRY AT INTERFACES

Theoretical analysis and measurements by means of thermoluminescent LiF at plane interfaces between a low Z-material and Al, Cu, Sn or Pb irradiated with 100 to 200 kV roentgen radiation

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INTRODUCTION

The dose distribution in soft tissue in contact with a medium of different atomic composition has been for a long time a matter of considerable interest. For high energy roentgen and gamma rays, extensive experimental investigations have been carried out over a wide range of atomic numbers (DUTREIX & BERNARD 1965, DUTREIX *et coll.* 1965, DUTREIX & BERNARD 1966, KRÜGER *et coll.* 1966). For low energy roentgen rays, interest has been concentrated on bone-soft tissue interfaces and glass- or plastic-soft tissue interfaces. These problems have been investigated both theoretically (SPIERS 1949, MUNSON 1950, SPIERS 1951, EPP *et coll.* 1959, CHARLTON & CORMACK 1962, SINCLAIR 1962, ASPIN & JOHNS 1963, HOWARTH 1965) and experimentally (STENSTROM & MARVIN 1946, WOODARD & SPIERS 1953, FOWLER 1957, MORKOVIN & FELDMAN 1959, FELDMAN & MORKOVIN 1960, HOOD & NORRIS 1961, WINGATE *et coll.* 1962, ASPIN & JOHNS 1963, HENDEE & KENNEDY 1967, LENTSCH & FINSTON 1967, SCHULZ 1968, ZANELLI 1968, and others). When irradiated with low energy roentgen rays, the absorbed dose in soft tissue in contact with materials of higher atomic number, Z , is raised above the electronic equilibrium absorbed dose in the same photon fluence because of the larger cross section for photoelectric absorption in the high Z material than in soft tissue. Knowledge of the dose distribution in soft tissue in contact with a medium of $Z > 14$ is limited (GRAY 1940, PATERSON 1942, ASPIN & JOHNS 1963, KRAMER 1966) since these cases have been supposed to be of little interest in radiology. However, when contrast media are used for roentgen diagnostic examinations, interfaces between soft tissues and such high Z materials as Ba ($Z=56$) and I ($Z=53$) are introduced into the body. In dental diagnostic procedures, the roentgen rays pass through soft tissues in contact with very high Z materials as Hg ($Z=80$) and Au ($Z=79$). Since the cross section for photoelectric absorption increases rapidly with the atomic number of the medium, the over-dosage of the soft tissue is expected to increase with increasing atomic number of the adjacent material. In the present work an experimental investigation of the dose distribution in a low Z material in contact with a material of higher Z has been made for 100 to 200 kV roentgen radiation using thermoluminescent LiF detectors. The Z -values ranged from $Z=13$ (Al) to $Z=82$ (Pb).

SURVEY OF THE PRESENT STATE

General aspects

Consider a beam of monoenergetic photons passing perpendicularly through an interface separating two media, 1 and 2, of different atomic numbers, Z_1 and Z_2 , respectively. R_1 and R_2 are the corresponding ranges of the most energetic secondary electrons (Fig. 1). At the interface a transition region exists where the electron fluence changes from its equilibrium value in medium 1 to its equilibrium value in medium 2. The transition region extends over a distance R_1 into medium 1 and over a distance R_2 into medium 2. (The primary photons are supposed to be of such energy that the photon fluence is approximately constant throughout the transition region, i.e. the mean free path of the photons $\frac{1}{\mu} \gg R$.) The resulting change in electron fluence produces a change in the absorbed dose within the transition region. For low energy photons, the secondary electron fluence in both media is due to photo- and Compton electrons. Since the cross section for photoelectric absorption increases rapidly with increasing atomic number, the equilibrium fluence of electrons in a high Z material is very much larger than the corresponding fluence in a low Z material for the same incident photon fluence. Even when the photons are of such energy that the Compton process dominates in both media, the equilibrium electron fluence is higher in a medium of high Z than in a medium of lower Z in the same photon fluence because of the decrease in stopping power per electron with increase of the atomic number of the stopping medium. While this statement is valid in every energy interval, the excess fluence of electrons is most marked at the low energy end of the spectrum, particularly when the contribution from δ -rays is included (SPENCER & FANO 1954, MCGINNIES 1959). Thus the absorbed dose in a small element (Bragg-Gray cavity) of a low Z material traversed by the equilibrium fluence of electrons existing in a high Z material is always larger than the absorbed dose under electronic equilibrium conditions in the low Z -material irradiated with the same photon fluence, as can also be deduced from cavity ionization theories and measurements (BURLIN 1968). Though there exist extensive calculations of the equilibrium spectra (slowing down spectra) of the secondary electrons (SPENCER & FANO 1954, MCGINNIES 1959), similar calculations,

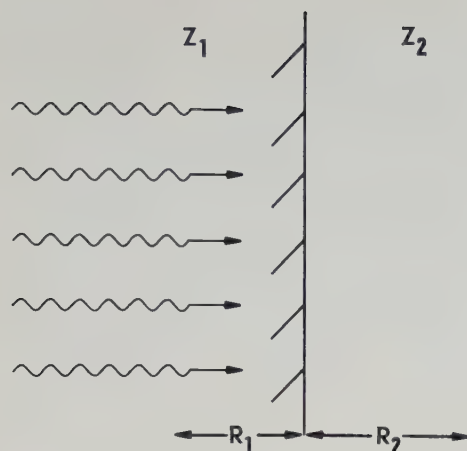


Fig. 1. Ranges of the most energetic secondary electrons, R_1 and R_2 , define the transition region at an interface irradiated with roentgen rays.

i.e. based on transport equations or using Monte Carlo techniques, of the change in the number and energy distributions of electrons at the boundary between different media are still rare (BERGER 1963). The accuracy of such calculations depends, moreover, upon the accuracy of available cross sections. Thus, for example, discrepancies between the calculated and the experimentally estimated spectra of slowing down electrons are partly ascribed to the failure of the Möller cross section to represent the actual electron scattering cross section at low electron energies (SPENCER 1971).

Simplified theories applied to interface dosimetry

The theories which have so far been applied to the problem in finding the dose distribution at an interface separating two different media have been mainly developed in order to calculate the absorbed dose in soft tissues in near contact with bone (or equivalent materials) and include some simplifying assumptions about the secondary electrons. Thus, the secondary electrons are assumed (1) to be emitted isotropically from the point at which the photons are absorbed and (2) to travel in straight lines; (3) an additional assumption concerns the ratio between the straight line ranges of the electrons in the two media. SPIERS (1949, 1951), CHARLTON & CORMACK (1962), HOWARTH (1965) assume this ratio to be equal to the inverse ratio of the electron stopping powers in the two media. The stopping power ratio is thereby regarded as being independent of the electron energy, a good approximation when the media do not differ more in

atomic composition than bone and soft tissue. CHARLTON (1970) assumes the ratio between the straight line ranges to be equal to the ratio between the full rectified ranges, calculated by using the continuous slowing down approximation (c.s.d.a.), of the electrons in the two media. This ratio is equal to the inverse ratio of the stopping powers in a case where the stopping power ratio is independent of the electron energy. The assumption adopted by CHARLTON (1970) provides a method of extending the theory to cases in which the stopping power ratio varies markedly with electron energy. The energy dependence of the stopping power ratio increases with increasing difference in the atomic composition of the two media. ASPIN & JOHNS (1963) extended their calculations to interfaces between lead glass and water, two media differing considerably in atomic composition. They assume the ratio between the straight line ranges to be equal to the inverse ratio of the stopping powers of the starting energy of the secondary electrons. Both versions of assumption (3) (CHARLTON and ASPIN & JOHNS) give the straight line range ratio as a function of the starting energy of the electrons but yield differing numerical values for this ratio. Furthermore the theories differ in their assumptions (4) about the actual length of and mode of energy deposition along the presumed straight track in soft tissue. This assumption influences the shape of the estimated dose gradient within the transition region, i.e. yields the so called geometrical or influence function. A comprehensive description of the theories is given by SPIERS (1969).

Numerical evaluations of absorbed doses in soft tissues adjacent to bone (or an equivalent material) have been performed for different interface geometries: plane, cylindrical and spherical, and for a wide range of photon energies: 30 to 250 kV roentgen radiation, ^{60}Co gamma rays and 22 MV roentgen rays (SPIERS 1949, 1951, EPP et coll. 1959, CHARLTON & CORMACK 1962, SINCLAIR 1962, ASPIN & JOHNS 1963, HOWARTH 1965).

As a consequence of assumptions (1) to (3), the calculated absorbed dose in soft tissue at a point close to a plane interface between thick slabs of bone and soft tissue is the sum of half of the dose in soft tissue under electronic equilibrium in soft tissue and half of the dose to a small soft tissue element traversed by the equilibrium electron fluence in bone. Characteristic features of the results obtained on basis of the assumptions (1) to (3) are thus that soft tissues in contact with bone are always overdosed, independent of photon energy and of the direction of the photon beam.

Earlier experiments

Dose distributions measured with an extrapolation chamber at plane bone-soft tissue interfaces (WINGATE et coll. 1962) irradiated with roentgen radiation,

30 kV to 210 kV, are in reasonably good agreement with the calculated dose distributions (HOWARTH 1965). Dose distribution measurements by means of induced conductivity in polyethylene (FOWLER 1957, LENTSCH & FINSTON 1967), corresponding to dose distributions in fat adjacent to plane bone interfaces give further support to the approximate validity of the theoretical results in this energy region. However, experiments with ^{60}Co gamma rays (KRÜGER et coll. 1966) show that soft tissue in contact with bone is underdosed when the photon beam passes perpendicularly through a plane bone-soft tissue interface and is overdosed when the beam passes in the opposite direction in disagreement with the theoretical results of EPP et coll. (1959), and SINCLAIR (1962). This is mainly due to that assumption (1) no longer holds for high energy photons. The secondary electrons are emitted predominantly in the forward direction. Since the Rutherford scattering of the electrons is higher in bone than in soft tissue, the secondary electrons generated in bone deviate more from their initial forward direction during the slowing down process than do those generated in soft tissue. Thus, at the plane bone-soft tissue interface the secondary electrons generated in the bone and escaping into the soft tissue do not fully compensate for the electrons generated in the soft tissue which escape into soft tissue, resulting in the observed underdosage of the soft tissue close to the bone-soft tissue interface. When, however, the beam passes in the opposite direction, through a plane soft tissue-bone interface, even the soft tissue dose from electrons generated in the soft tissue exceeds the dose to soft tissue under electronic equilibrium conditions due to the increased backscattering of the electrons when impinging on the higher Z material (DUTREIX & BERNARD 1965).

Limitations of the simplified theories: photon energy and atomic number

Because of assumption (1) the theories yield realistic results only for low energy photons. Because Rutherford scattering of the electrons increases strongly with the atomic number of the absorber, assumption (3) is less valid the higher the atomic number of the adjacent material. For this reason the theories are also limited with regard to the atomic number of the adjacent material, the degree of limitation being dependent on the interface geometry. Assumption (3) (ASPIN & JOHNS 1963, CHARLTON 1970) is such that the theory overestimates the depth from which electrons emitted in a high Z material can actually reach the interface, resulting in an overestimate of the fluence of electrons passing from the high Z into the low Z material. Thus, at a plane interface the absorbed dose in soft tissue from electrons generated in the high Z material is likely to be overestimated. For soft tissue inside a cavity surrounded by a high Z material

the overestimate will be less since scattering of the electrons between the cavity walls, neglected in the theoretical treatment, compensates for the overestimate of the generation depth. With decreasing dimensions of the spherical and cylindrical cavities, the theories yield a value of the mean absorbed dose in soft tissue inside the cavity which approximately approaches the Bragg-Gray dose to soft tissue: the mean absorbed dose in the soft tissue inside the cavity is related to the absorbed dose in the wall material through the value of the straight line range ratio entering into assumption (3). In the Bragg-Gray theories, the corresponding relation is given by a weighted mean of the inverse ratio of the stopping powers (or restricted stopping powers, SPENCER & ATTIX 1955) with the absorbed dose from the electrons in the slowing down spectrum as a weighing factor.

ASPIN & JOHNS (1963) calculated the mean absorbed dose in water inside cylindrical cavities of pyrex glass and lead glass. With ^{60}Co gamma radiation the mean absorbed dose did not vary with the radius of the capillaries used. This fact indicates that the capillaries were approximately Bragg-Gray cavities. The deviation between their calculated and experimental results can partly be attributed to their use of the stopping power ratio of the starting energy of the electrons, resulting in an underestimate of the Bragg-Gray dose.

Treatment of fluorescence radiation

Theoretic calculations of the absorbed dose to soft tissue adjacent to a high Z material irradiated with low energy photons are further complicated by the difficulties of taking into account the effect of the fluorescence radiation emitted following photoelectric absorption. In the case of a bone-soft tissue interface, the fluorescence radiation has been assumed to escape from the region of interest (CHARLTON & CORMACK 1962) or to be absorbed in the same way as the photoelectrons (HOWARTH 1965). Neither assumption leads to large errors since the fluorescence yield is low. As the mean free path in soft tissue of the fluorescence photons is of the same order of magnitude as the range of the photoelectrons liberated by the primary photons, the latter assumption seems the more realistic. With increasing Z, however, the fluorescence yield increases and the mean free path in soft tissue of the fluorescence photons is appreciably longer than the range of the photoelectrons even if it is not long enough to give a negligible contribution to the soft tissue dose within the transition region. Since the fluorescence photons are isotropically emitted, this contribution to the dose also depends on the size of the primary radiation field. The effect of the fluorescence photons at the interface can in principle be accounted for by treat-

ing the fluence of these photons separately and adding it to the fluence of the primary photons. It is, however, obvious that by the inclusion of a geometry-dependent fluence of fluorescence photons, the calculations become considerably more complex.

In the calculations by ASPIN & JOHNS (1963) their treatment of the fluorescence radiation emitted within lead glass has not been discussed. It seems as if the binding energy of the photoelectrons, appearing as fluorescence radiation and Auger electrons, has been regarded as escaped from the volume of interest. Thus, their conclusions about the agreement between the theoretical and experimental results are doubtful.

The present experimental work has been carried out in two steps. In the first part, dose distributions outside the transition region due to fluorescence radiations have been examined, while in the second part, attempts have been made to estimate the dose distribution within the transition region.

PRESENT EXPERIMENTS

Arrangements

Detectors

Discs of thermoluminescent LiF embedded in teflon, $(C_2F_4)_n$, 0.13 mm thick and 13 mm in diameter, were used (BJÄRNGÅRD et coll. 1967). During readout the detectors were placed on a heating element (planchette) of stainless steel.

Phantom material

The introduction of a LiF-teflon detector into a soft tissue equivalent phantom produces an inhomogeneity since the density ($\rho_{LiF}=2.6 \text{ g/m}^3$, $\rho_{(C_2F_4)_n}=2.2 \text{ g/cm}^3$) and effective atomic number of the detector are higher than those of soft tissue. To minimize the distortion of the photon radiation field in which the dose distribution is to be measured, as few detectors as possible should be used in each irradiation. The variation with depth, i.e. with radiation spectrum, of the energy absorption in the detector relative to that in soft tissue must be corrected for. For this investigation a teflon phantom was used. The phantom-detector system is then homogeneous enough to allow a close packing of the detectors in the phantom, and the variation with depth of the energy absorption in LiF relative to that in teflon is negligible (Fig. 6).

Radiation sources

A ^{137}Cs teletherapy unit was used for calibration purposes. A roentgen tube with maximum 300 kV acceleration potential was used in the depth dose measurements. Spectra of the roentgen radiation at 100 kV and 200 kV acceleration potential, respectively, are given in Fig. 3.

Irradiation geometry

The central axis of the radiation beam was directed perpendicularly towards the surface of an approximately cubic phantom made of 12 teflon plates, each $11.5 \text{ cm} \times 11.5 \text{ cm} \times 0.9 \text{ cm}$. The entrance field, symmetrically situated on the phantom surface, was $3 \text{ cm} \times 3 \text{ cm}$ and was defined by means of a lead mask.

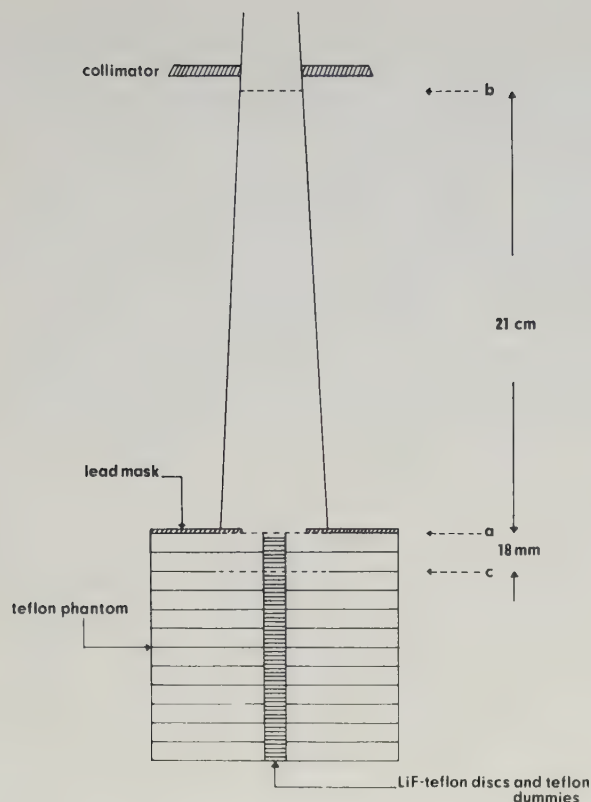


Fig. 2. Irradiation geometry. a), b) and c) show the places where metal foils were introduced.

The focus-surface distance was 50 cm. Metal foils of Al, Cu, Sn and Pb were inserted into the beam (a) on the surface of the phantom, (b) parallel to the phantom surface and raised 21 cm above the surface, and (c) parallel to phantom surface at a depth of 18 mm beneath the surface. In all cases the metal foils covered the whole beam area. The measurements of the dose distribution within the transition region (at the metal foil-phantom interface) were performed with the metal foil in position (a).

Spectra of photons transmitted through various metal foils

The thickness of the metal foils was chosen so that for all values of Z the electronic equilibrium absorbed dose in LiF from the transmitted primary photons was the same fraction of the electronic equilibrium absorbed dose in LiF from the primary photons impinging on the foils. Calculations to give the appropriate thickness of the foils were carried out using data on the primary photon spectra (HETTINGER & STARFELT 1958), attenuation coefficients for Al,

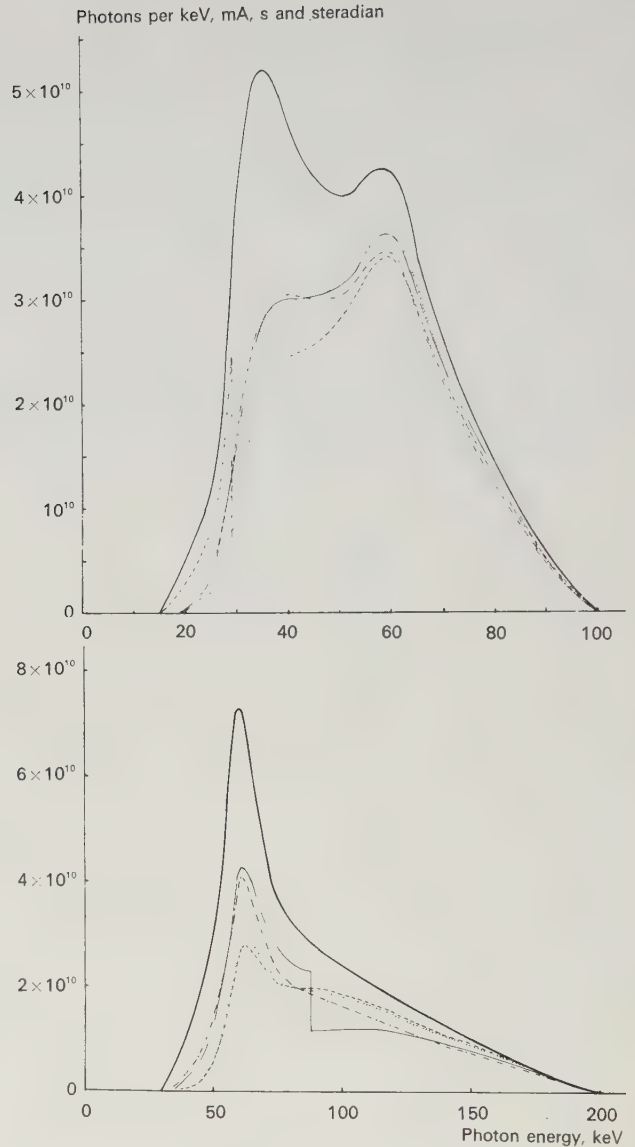


Fig. 3. Spectra of the primary photons and of those transmitted by the various metal filters. The electronic equilibrium absorbed dose in LiF from the transmitted primary photons is the same with all metal foils. a) (above) 100 kV, 4 mm Al-filter — b) (below) 200 kV, 0.5 mm Cu-filter — a) and b) added filters of Pb —, Sn ----, Cu ·····, and Al - - - -.

Cu, Sn, Pb and energy absorption coefficients for LiF (HUBBELL 1969). The calculated thicknesses were for 100 kV: Pb=0.030 mm, Sn=0.046 mm, Cu=0.103 mm, Al=2.85 mm, and for 200 kV: Pb=0.11 mm, Sn=0.22 mm, Cu=0.69 mm, Al=8.7 mm. The absorbed dose from the transmitted primary photons was then 61 per cent of the absorbed dose from the impinging primary photons.

Spectra of the primary beam and the extra filtered beams are given in Fig. 3 for the two radiation qualities used. The discontinuities in the spectra of photons transmitted through Sn and Pb with 100 kV and 200 kV, respectively, are due to the K-edges of Sn (29 keV) and Pb (88 keV).

Methods of measurement

As the thickness of the LiF-teflon discs is small compared to the mean free path of the photons but very large compared to the range of the secondary electrons (0.13 mm LiF-teflon equals the pathlength of a 140 keV electron, BERGER & SELTZER 1964, 1966) different methods have been used when measuring depth doses beyond and within the transition region.

Depth doses beyond the transition region

Situated symmetrically around the central axis, with their diameters perpendicular to the incoming photon beam (Fig. 2), the LiF-teflon discs are given a homogeneous or slightly varying dose, i.e. they function as dosimeters. A complete depth dose distribution was measured with a single irradiation.

To yield measurements with high precision, the dosimeters were individually calibrated following a technique described elsewhere (CARLSSON et coll. 1968).

High temperature preannealing occurred only during readout, during which the dosimeters reached about 310°C within 10 s and returned to room temperature within 1 min. After readout, they were stored at room temperature until the next irradiation provided the time interval at room temperature did not exceed 4 h. In this case the readout process was repeated without foregoing irradiation. The time interval between irradiation and readout of a particular dosimeter was the same in both calibration and experiment thus eliminating the effects of fading. The preannealing method used results in the glow curve being unfavourable as regards its fading characteristics. However, if the fading can be controlled by a standardized thermal treatment scheme as described above, this preannealing method has the advantage that the dosimeters can be used again immediately after readout. Furthermore, the relative standard deviation of the measurements can be kept as low as 0.3 per cent (MÄRTENSSON 1969). Radiations with different LET-distributions were used in the calibration with ^{137}Cs gamma radiation and in the measurements. To avoid the effects of induced LET-dependence (CARLSSON & ALM CARLSSON 1968, SUNTHARALINGAM & CAMERON 1969) it is essential that dosimeters calibrated together have the same radiation history. Thus, in repeated depth dose measurements with the same group of individually calibrated dosimeters, each dosimeter was placed at dif-

ferent depths from time to time in order to smooth out the differences in radiation history caused by depth doses. The calibration procedure was repeated before every depth dose measurement.

Depth doses within the transition region

The dose distribution was resolved by successively increasing the number of thin mylar, $(C_{10}H_8O_4)_n$, films 0.486 mg/cm^2 thick, between the metal foil and the nearest LiF-teflon disc.

Efforts to produce microdiscs of LiF-teflon have been made by other investigators. SCHULZ (1968) succeeded in producing $10 \text{ }\mu\text{m}$ thick LiF-teflon discs. The effective thickness of such a disc is, however, $\simeq 2.0 \text{ mg/cm}^2$, so that the spatial resolution is more than four times better with the mylar films as used here than with microdiscs.

Principles of the method. In the following the detector-phantom system and the interposed thin films are assumed to be of identical materials. Furthermore, the absorbed dose in the detector is assumed to vary in one direction only, i.e. with depth.

The detector signal, M_i , as a function of the number i of interposed films of thickness Δt is given by

$$M_i = \eta \cdot \int_{i \cdot \Delta t}^{T + i \cdot \Delta t} D(t) A dt \quad (1)$$

where

η = the detector signal per unit absorbed energy in the detector (=the efficiency of the detector)

$D(t)$ = the absorbed dose at depth, t , from the metal foil

A = the area of the detector

T = the thickness of the detector (given as mass per unit area)

With $i \cdot \Delta t \geq R$, where R = the range of the most energetic secondary electrons, the detector signal, M_{eq} , is given by

$$M_{eq} = \eta \cdot D_{eq} \cdot A \cdot T \quad (2)$$

where D_{eq} = the absorbed dose under electronic equilibrium conditions.

On the other hand, for $i \cdot \Delta t < R$ the mean absorbed dose, $\bar{D}_{i+1}$, in the film number $i+1$ is, as the detector thickness $T > R$, derived from

$$M_i - M_{i+1} = \eta \cdot A \cdot \Delta t [\bar{D}_{i+1} - D_{eq}] \quad (3)$$

From eqs (2) and (3)

$$\frac{\bar{D}_{i+1}}{D_{eq}} = (M_i - M_{i+1}) \frac{T}{M_{eq} \cdot \Delta t} + 1 \quad (4)$$

Experimental method. Eq. (1) is valid for a detector with the same efficiency, η , over all depths of the detector. For the thermoluminescent LiF-teflon discs this may not be the case due to (1) supralinearity effects, (2) sensitizing or radiation damage effects appearing in repeated use, (3) LET-variations with depth of the absorbed radiation, and (4) the construction of the discs.

(1) and (2): Due to the photoelectrons liberated in the metal foil, the absorbed dose, $D(t)$, varies considerably with depth, t , in the detector. In some cases, $D(0)$ can be as much as 50 times more than D_{eq} . The efficiency η may vary with depth due to supralinearity (NAYLOR 1965, CAMERON et coll. 1967) in those layers of the detector absorbing the higher doses or due to induced effects as a higher degree of sensitizing or radiation damage (MARRONE & ATTIX 1964, DOPPKE & CAMERON 1966, CARLSSON & ALM CARLSSON 1968, SUNTHARALINGAM & CAMERON 1969) in those layers of the detector previously irradiated with higher doses. Supralinearity was avoided by using sufficiently small doses of D_{eq} , $D_{\text{eq}} \simeq 10 \text{ rad}_{\text{LiF}}$. (With ^{60}Co gamma rays, supralinearity was estimated to occur at absorbed doses of 400 to 600 rad_{LiF} . However, with radiations of higher LET, higher absorbed doses are required to cause supralinearity. With 275 to 400 keV electrons SUNTHARALINGAM & CAMERON reported that supralinearity occurred at 500 to 1000 rad_{LiF} while for 50 to 175 keV electrons supralinearity was not obtained until above 1000 rad_{LiF} .)

Induced effects can be avoided by using a detector only once. The M_i -signals were measured using different detectors for each number, i , of interposed films.

(3): There exists experimental (GORBICS & ATTIX 1968, TOCHILIN et coll. 1968, CARLSSON & ALM CARLSSON 1970) as well as theoretical (SUNTHARALINGAM & CAMERON 1969, CARLSSON & ALM CARLSSON 1970) evidence for a dependence of the efficiency on the LET within the actual LET-interval, also at low doses (=non-supralinear doses). Quantitative knowledge about this dependence is still vague. The LET-variation with depth is, however, supposed to be small due to the smoothing effect of broad LET-spectra at each depth.

(4): The LiF-grains may be of varying efficiencies as well as nonuniformly distributed within the teflon matrix. A dead layer (KASTNER et coll. 1967, ZANELLI 1968) of the LiF-grains would introduce a dead surface layer of the detectors. Furthermore, teflon is not fully transparent for the thermoluminescent light emitted. A correction for the lack of transparency was performed as described later.

Since different detectors were used for measuring the M_i -signals, eq. (4) is not directly applicable, mainly due to somewhat varying thicknesses, T_j , of the individual detectors, j . Furthermore, the efficiency varies individually with depth, t , in a specified detector, i.e. $\eta = [\eta(t)]_j$.

The experiment proceeded in the following steps, (a) to (e):

(a) A number, n , of LiF-teflon discs were homogeneously irradiated with 200 kV roentgen radiation, so that the same absorbed dose, D , was received by all the discs. The irradiation technique by means of a specially constructed teflon phantom, described by CARLSSON et coll. (1968), was used. Individual calibration constants, c_j , were then calculated from

$$c_j = \frac{\frac{1}{n} \sum [M]_j}{[M]_j} = \frac{\bar{M}}{[M]_j} \quad (5)$$

where

$$[M]_j = A \cdot D \cdot \int_0^{T_j} [\eta(t)]_j dt \quad (6)$$

(b) Irradiation at the metal foil-phantom interface (Fig. 2, position a): three LiF-teflon discs, packed one closely behind the other, were irradiated simultaneously. The signals from the two detectors furthest away from the metal foil, i.e. situated outside the transition region, give, when corrected with their individual calibration constants, signals $\bar{M}_{eq}$ proportional to the electronic equilibrium absorbed dose. $\bar{M}_{eq}$ is given by a relation corresponding to eq. (2).

$$\bar{M}_{eq} = \bar{\eta} \cdot D_{eq} \cdot A \cdot \bar{T} \quad (7)$$

where $\bar{T}$ is the mean thickness of the individually calibrated detectors and $\bar{\eta}$ is a weighted mean of the individual mean efficiencies, $[\bar{\eta}]_j$, with the detector thickness, T_j , as a weighing factor, i.e.

$$\bar{\eta} \cdot \bar{T} = \frac{1}{n} \cdot \sum_0^{T_j} [\eta(t)]_j dt = \frac{1}{n} \cdot \sum [\bar{\eta}]_j \cdot T_j \quad (8)$$

(c) The signal $[M_i]_j$ from the detector nearest to the metal foil was divided into two terms, $[M_i]_j'$ and $[M_{eq}]_j$ (Fig. 4). Here, i =the number of interposed films and j =the identification number of the detector. $[M_{eq}]_j$ is obtained from $\bar{M}_{eq}$, estimated as described in (b), by means of the individual calibration constant c_j , estimated in (a):

$$[M_{eq}]_j = \frac{\bar{M}_{eq}}{c_j} \quad (9)$$

As $D(t) - D_{eq}$ is zero for all depths $t > R$, $[M_i]_j'$ is given by

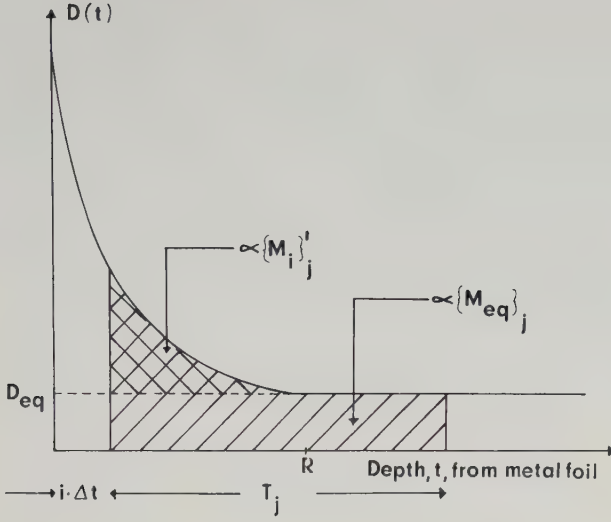


Fig. 4. Division of the absorbed energy in the j th detector into two terms. The corresponding partial detector signals are $[M_i]_j^i$ and $[M_{eq}]_j$.

$$[M_i]_j^i = A \cdot \int_{i \cdot \Delta t}^R [\eta(t - i \cdot \Delta t)]_j [D(t) - D_{eq}] dt \quad (10)$$

Eq. (10) shows that the partial signal $[M_i]_j^i$ is independent of the thickness, T_j , of the individual detector. Nevertheless, even with the same number, i , of interposed films, different detectors, j , yield varying signals $[M_i]_j^i$ (within ± 5 per cent).

(d) Surface calibration: the detectors were irradiated as in (b) close to a gold foil. Individual surface calibration constants, s_j , were calculated from

$$s_j = \frac{\frac{1}{n} \cdot \Sigma [M_o]_j^i}{[M_o]_j^i} = \frac{\bar{M}_o^i}{[M_o]_j^i} \quad (11)$$

Here n is the number of surface calibrated detectors.

$\frac{1}{s_j}$ yields the relative weighted average efficiency of the surface layers with the dose gradient, $D(t) - D_{eq}$, predominantly from the photoelectrons generated in gold as a weighing factor, i.e.

$$\frac{1}{s_j} = \frac{[\bar{\eta}_o]_j^i}{\frac{1}{n} \cdot \Sigma [\eta_o]_j^i} \quad (12)$$

where

$$[\bar{\eta}_0]_j' = \frac{R \int_0^{\bar{T}} [\eta(t)]_j \cdot [D(t) - D_{eq}] dt}{R \int_0^{\bar{T}} [D(t) - D_{eq}] dt} \quad (13)$$

(e) $\bar{M}'_i = s_j \cdot [M_i]_j'$ was plotted as a function of i and smoothed $\bar{M}'_i$ -values were used in an equation equivalent to eq. (4)

$$\frac{\bar{D}_{i+1}}{D_{eq}} = (\bar{M}'_i - \bar{M}'_{i+1}) \cdot \frac{\bar{T}}{\bar{M}_{eq} \cdot \Delta t} + 1 \quad (14)$$

where $\bar{M}_{eq}$ and $\bar{T}$ are defined in (b).

By using the detectors twice, in the surface calibration and in the experiment, radiation induced effects from the surface calibration should be eliminated before the experiment. (The surface calibration was in general performed before the experiment.) By investigating the quantity

$$\frac{\bar{M}'_o}{\bar{M}_{eq}/\bar{T}} = \frac{\frac{1}{n} \cdot \sum [\bar{\eta}_0]_j'}{\bar{\eta}} \cdot R \int_0^{\bar{T}} \left[\frac{D(t)}{D_{eq}} - 1 \right] dt \quad (15)$$

in repeated surface calibrations, any change in the mean weighted average efficiency of the surface layers relative to the mean efficiency, $\bar{\eta}$, over all depths of the detectors, could be detected. By appropriate choice of the preannealing method, the change in the above quantity, eq. (15), could be kept within ± 1 per cent, $n=10$, in two repeated calibrations. Repeating the calibrations several times caused this quantity to decrease, probably due to a radiation damage of the surface layers. As preannealing, the detectors were twice taken through the readout process using a higher heating current than normal. The temperature in the detector reached about 340°C to 370°C for a few seconds. Storing the detectors in 340°C to 350°C for 24 h eliminates sensitizing but caused greater statistical fluctuations in the individual efficiencies $[\bar{\eta}_0]_j'$, in accordance with the results of MÅRTENSSON (1969).

The individual dose calibration described in (a) was performed before the surface calibration as well as before the experiment. To ensure that the individual calibration constants, estimated in (a), are really valid when used as described in (c), 200 kV roentgen radiation was used for the individual calibration instead of the usual ^{137}Cs gamma radiation. In spite of the precautions taken to avoid sensitizing effects remaining from the surface calibration there could, in prin-

ciple, exist an individually varying induced LET-dependence in the detectors and the effect of an induced LET-dependence is especially marked when the LET-distribution is changed from that of the ^{137}Cs gamma radiation to those of the roentgen qualities used in this investigation (CARLSSON & ALM CARLSSON 1968).

Eq. (15) was also used to normalize measurements with different sets of detectors to each other.

Difficulties of the measurements in the transition region

Systematic errors due to the detector construction

The corrected signals $\bar{M}'_i$ are obtained from

$$\bar{M}'_i = s_j \cdot [M_i]'_j = \frac{\frac{1}{n} \cdot \Sigma [\bar{\eta}_0]'_j}{[\bar{\eta}_0]'_j} \cdot [\bar{\eta}_i]'_j \cdot A \cdot \int_{i \cdot \Delta t}^R [D(t) - D_{eq}] dt \quad (16)$$

Here s_j is given by eq. (12) and $[M_i]'_j$ is defined in eq. (10). $[M_i]'_j$ can also be written as in eq. (16) above, in which case $[\bar{\eta}_i]'_j$ is defined similarly to $[\bar{\eta}_0]'_j$ in eq. (13) by changing the lower limit of integration from zero to $i \cdot \Delta t$. By assuming that $[\bar{\eta}_0]'_j = [\bar{\eta}_i]'_j$, all i , $\bar{M}'_i$ and $\bar{M}'_{i+1}$ in eq. (14) are determined with an efficiency given by

$$\eta'_0 = \frac{1}{n} \cdot \Sigma [\bar{\eta}_0]'_j \quad (17)$$

This assumption is more valid the lower the number, i , of interposed films. Due to the shape of the dose gradient the efficiency of the outermost surface layer has a much greater weight than the others so that the assumption should be rather good for small values of i . Furthermore, as the surface calibrations were performed with gold, $[\bar{\eta}_0]'_j$ in eq. (16) applies for gold while $[\bar{\eta}_i]'_j$ applies to the metal used in the measurement. Such a difference is supposed to be of less importance, provided the quality of the primary photon radiation is the same in the two cases. Gold, i.e. a high Z material, was chosen for the surface calibrations to minimize the statistical fluctuations in the estimated calibration constants.

The main difficulty which could not be resolved experimentally lies in the fact that $\bar{M}'_i$ and $\bar{M}'_{eq}$ used with eq. (14) may have been measured with different efficiencies, $\bar{\eta}'_0$ and $\bar{\eta}'_i$, respectively, so that the first term in eq. (14) should have to be corrected with a factor $\bar{\eta}'_0/\bar{\eta}'_i$. By using many detectors instead of only one

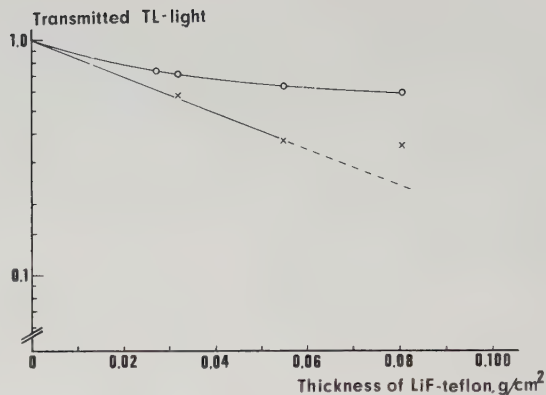


Fig. 5. Fraction of thermoluminescent light transmitted through layers of LiF-teflon of varying thickness ($\times$ — $\times$). The transparency increases when LiF-teflon is stored at 340 to 350°C for 24 h ($\circ$ — $\circ$). The thickness of one LiF-teflon detector ≈ 0.03 g/cm².

the influence of a purely random distribution of LiF-grains in the detectors on the efficiencies $\bar{\eta}_0$ and $\bar{\eta}$ is smoothed. A systematic deviation of the concentration and mean efficiency of the LiF-grains at the surface of the detector cannot, however, be excluded. A dead layer in the LiF-grains would result in a relatively low weighted average efficiency of the surface layers due to the large weight of the outermost surface layer. Such a dead layer can also be regarded as introducing an extra fictitious thin film $\Delta t'$ between the real detector and the metal foil.

Correction for the attenuation of the thermoluminescent light in the detector

The LiF-teflon detectors are not quite transparent for the thermoluminescent light emitted. The transparency increases after storage of the detectors at 340°C to 350°C for 24 h (Fig. 5).

The transmission curves in Fig. 5 were measured by reading out irradiated detectors with nonirradiated LiF-teflon discs of varying thickness on the top. The attenuation of the light is mainly due to the teflon part of the discs, so that possible variations in the LiF-content of discs of different thickness influence upon the transmission curves.

In readout, that side of the detector which had been irradiated with the photoelectrons from the metal foil was turned away from the light measuring device (PM-tube). The light emitted due to the absorption of these photoelectrons is thus relatively more attenuated before it is measured than the light emitted from a homogeneously irradiated detector. The reduction of the emitted light before registration also depends on the reflecting power of the planchette. Moreover, not all of the light escaping from the surface of the detector is registered

in the PM-tube. Due to the geometrical arrangement of the detector and the PM-tube, only light emitted within an angle of about 30° to the normal to the detector surface reaches the PM-tube. In the following discussion, the fraction of the emitted light which has the possibility of being detected is considered to have been emitted perpendicularly to the detector surface.

The signals $\bar{M}'_i$ and $\bar{M}'_{eq}$ to be used with eq. (14) are the true detector signals, i.e. are the signals which would be obtained without the attenuation and reflection losses of the light emitted before recording. The signals actually recorded are denoted by $\bar{S}'_i$ and $\bar{S}'_{eq}$, respectively. These signals must be corrected to yield the true detector signals. Correction factors were estimated by using the following assumptions: (a) At 100 kV the penetration depth of the photoelectrons is negligible. (b) In a homogeneously irradiated detector, the true detector signal per unit length is constant $= \bar{M}'_{eq}/\bar{T}$. (c) The thermoluminescent light emitted from a thin layer of the detector as well as the light reflected from the planchette is exponentially attenuated in traversing the detector, the attenuation coefficient, k , being given by the transmission curves in Fig. 5. (d) A fraction x of the thermoluminescent light incident on the planchette is reflected.

Then

$$\bar{S}'_i = \frac{\bar{M}'_i}{2} \cdot e^{-k\bar{T}} \cdot (1+x) \quad (18)$$

$$\bar{S}'_{eq} = \frac{\bar{M}'_{eq}}{2k\bar{T}} \cdot [1 - e^{-k\bar{T}} \cdot (1-x) - x \cdot e^{-2k\bar{T}}] \quad (19)$$

Thus, when the recorded signals $\bar{S}'_i$ and $\bar{S}'_{eq}$ are used with eq. (14) the first term of eq. (14) must be corrected by a factor

$$\frac{1 - e^{-k\bar{T}} \cdot (1-x) - x \cdot e^{-2k\bar{T}}}{k\bar{T}(1+x) \cdot e^{-k\bar{T}}} \quad (20)$$

To estimate the unknown parameter x , the detectors were also read out with that side irradiated with the photoelectrons from the metal foil towards the PM-tube. The signal then recorded, $[\bar{S}'_i]_{\text{towards}}$, is given by

$$[\bar{S}'_i]_{\text{towards}} = \frac{\bar{M}'_i}{2} [1 + x \cdot e^{-2k\bar{T}}] \quad (21)$$

The quotient between $[\bar{S}'_i]_{\text{towards}}$ and $\bar{S}'_i$, m , is given by

$$m = \frac{1 + x \cdot e^{-2k\bar{T}}}{e^{-k\bar{T}} \cdot (1 + x)} \quad (22)$$

m was determined by irradiating the detectors with the photoelectrons emitted from gold without interposed films, i.e. $i=0$. With unprepared detectors, $m=1.41$ while after the detectors had been stored at 340°C to 350°C $m=1.12$. x was thus estimated to be 0.5. (To keep x constant throughout the experiments the planchette was repeatedly cleaned by storing it in hydrogen peroxide when not in use.) Ultimately the correction factor given by eq. (20) was estimated to be 1.17 and 1.05 for the unprepared and the more transparent detectors, respectively.

With 200 kV the values of m are, when determined in the same way as with 100 kV, somewhat smaller due to the increased ranges of the photoelectrons. In this case, $m=1.31$ and $m=1.09$ as compared to $m=1.41$ and $m=1.12$ with 100 kV. With 200 kV the recorded signals $\bar{S}'_i$ and $\bar{S}_{\text{eq}}$ were used with eq. (14) and the first term was multiplied with a factor estimated to be 1.16 and 1.05 for the unprepared and the more transparent detectors, respectively. The correction factor was then taken as $(1+m)/2$, using the above value of m . This is the same as assuming that the attenuation and reflection losses of the emitted light in the homogeneously irradiated detector are compensated for by using the mean value of $\bar{S}'_o$ and $[\bar{S}'_o]_{\text{towards}}$.

As is evident from the above, the same correction factor was applied independent of the number of films interposed. With both 100 kV and 200 kV, however, the depth dose distributions measured with unprepared detectors did not deviate significantly from the depth dose distributions measured with the more transparent detectors. Thus, the increasing relative reduction of the true detector signals $\bar{M}'_i$ with increasing number of interposed films is of minor importance compared to other factors influencing the precision of the measurements.

Radiation absorption and electron scattering properties of mylar and LiF-teflon. Influence upon the interpretation of the experimental results

Analysis of the detector signal caused by absorption of electrons generated in three different media. The detector and the interposed films do not in fact have identical radiation absorption properties as has so far been assumed. In Figs 6 and 7 the photon mass energy absorption coefficients and electron collision mass stopping powers of mylar, $(\text{C}_{10}\text{H}_8\text{O}_4)_n$, LiF and teflon, $(\text{C}_2\text{F}_4)_n$, are compared to those of muscle.

The different radiation absorption properties, as well as the differences in electron scattering properties, of mylar and LiF-teflon complicate the interpre-

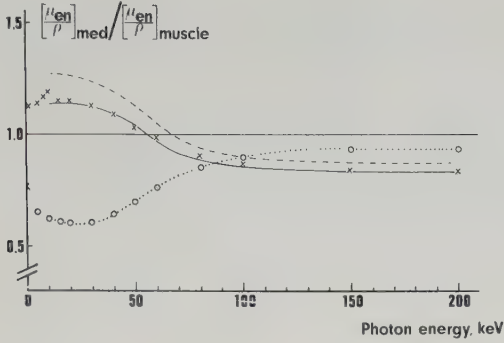


Fig. 6. Relative mass energy absorption coefficients for LiF (—), teflon (---) and mylar (····) as a function of photon energy. The mass energy absorption coefficients are calculated from HUBBELL (1969). Relative mass energy absorption coefficients for LiF (×) and mylar (o), calculated from the more recent tabulations by STORM & ISRAEL (1970), are included. The composition of muscle was taken from ICRU 1964.

tation of the results obtained by using eq. (14). The decrease in the signals $\bar{M}'_i$ with increasing number i of interposed mylar films is mainly, but not exclusively, related to the stopping in these films of the electrons generated in the metal foil, while $\bar{M}'_{eq}$ is proportional to the electronic equilibrium absorbed dose in LiF, $D_{eq,L}$. The aim of the following analysis is to find the means to convert the results of eq. (14) to yield relative depth doses in a homogeneous material.

Electrons generated in three different media: the metal foil (Z), the mylar films (m), and LiF-teflon (L), deposit energy in the detector. The absorbed energy, $\bar{\varepsilon}_i$, in the detector with i interposed mylar films can be divided into three terms:

$$\bar{\varepsilon}_i = \sum_{k=Z,m,L} [\bar{\varepsilon}_i]_k \quad (23)$$

where $[\bar{\varepsilon}_i]_k$ is the energy deposited in the detector by electrons generated in the medium k .

The $\bar{M}'_i$ -signals, eq. (16), can in terms of the $[\bar{\varepsilon}_i]_k$ defined above be written

$$\bar{M}'_i = \bar{\eta}^1_0 \cdot ([\bar{\varepsilon}_i]_Z + [\bar{\varepsilon}_i]_m + [\bar{\varepsilon}_i]_{L,j} - D_{eq,L} \cdot A \cdot T_j) \quad (24)$$

Here $[\bar{\varepsilon}_i]_{L,j}$ is the absorbed energy in the j th detector from electrons generated in LiF-teflon. Due to variations in the thickness, T_j , of the individual detectors this quantity differs from one detector to another. The quantity $[\bar{\varepsilon}_i]_{L,j} - D_{eq,L} \cdot A \cdot T_j$ is however independent of the detector and can be written as $[\bar{\varepsilon}_i]_L - D_{eq,L} \cdot A \cdot R$ for all detectors. $[\bar{\varepsilon}_i]_L$ is then the absorbed energy in a detector of thickness R . As R is the range of the most energetic secondary electrons, $[\bar{\varepsilon}_i]_Z$ and $[\bar{\varepsilon}_i]_m$ are independent of the detector thickness, T , for $T \geq R$. The difference of the signals $\bar{M}'_i - \bar{M}'_{i+1}$ can then be written

$$\bar{M}'_i - \bar{M}'_{i+1} = \bar{\eta}^1_0 \cdot ([\bar{\varepsilon}_i]_Z - [\bar{\varepsilon}_{i+1}]_Z - \Delta \bar{\varepsilon}) \quad (25)$$

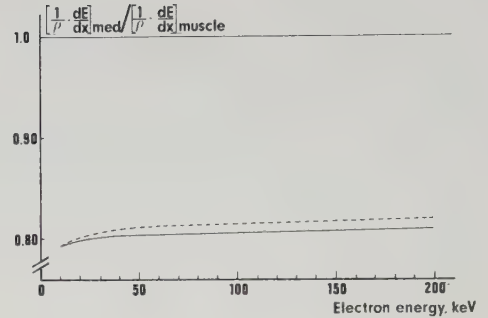


Fig. 7. Relative collision mass stopping powers of LiF (—), teflon (----) and mylar (····) as a function of electron energy. The collision mass stopping powers are taken from BERGER & SELTZER (1964, 1966). The composition of muscle was taken from ICRU 1964.

where $\Delta\bar{\varepsilon} \neq 0$ and is given by

$$\Delta\bar{\varepsilon} = [\bar{\varepsilon}_{i+1}]_m - [\bar{\varepsilon}_i]_m + [\bar{\varepsilon}_{i+1}]_L - [\bar{\varepsilon}_i]_L \quad (26)$$

$[\bar{\varepsilon}_{i+1}]_m > [\bar{\varepsilon}_i]_m$ for all i so that $i \cdot \Delta t < R$.

With increase in the number of interposed mylar films, an increasing number of electrons generated in the mylar reach the detector. Furthermore $[\bar{\varepsilon}_i]_L \geq [\bar{\varepsilon}_{i+1}]_L$. Here $[\bar{\varepsilon}_i]_L > [\bar{\varepsilon}_{i+1}]_L$ only for values of i so small that electrons generated in LiF-teflon can be scattered back into the detector by the metal foil. For values of i so large that the backscattering takes place exclusively in the mylar films, $[\bar{\varepsilon}_i]_L = [\bar{\varepsilon}_{i+1}]_L$.

Thus, provided that the efficiencies $\bar{\eta}'_o$ and $\bar{\eta}$ are equal, the first term of eq. (14) can be written

$$(\bar{M}'_i - \bar{M}'_{i+1}) \cdot \frac{\bar{T}}{\bar{M}_{eq} \cdot \Delta t} = \frac{[\bar{\varepsilon}_i]_Z - [\bar{\varepsilon}_{i+1}]_Z - \Delta\bar{\varepsilon}}{D_{eq,L} \cdot A \cdot \Delta t} \quad (27)$$

Conversion of the experimental results to relative depth doses in a homogeneous material. Relative depth doses in mylar. Consider a case where the number of interposed mylar films is so large that $i \cdot \Delta t = 2 \cdot R$. The relative depth doses in the first half of the mylar films, i.e. where only electrons generated in the metal foil and mylar are absorbed, can be written as

$$\frac{\bar{D}_{m,i+1}}{D_{eq,m}} = \frac{[\bar{D}_{m,i+1}]_Z + [\bar{D}_{m,i+1}]_m}{D_{eq,m}} \quad (28)$$

where

$[\bar{D}_{m,i+1}]_Z$ is the mean absorbed dose in the mylar film number $i+1$ from electrons generated in the metal foil, $[\bar{D}_{m,i+1}]_m$ is the corresponding mean absorbed dose from electrons generated in mylar, and $D_{eq,m}$ is the electronic equilibrium ab-

sorbed dose in mylar. Here $[\bar{D}_{m,i+1}]_m \leq D_{eq,m}$. Eq. (28) can be rearranged to read

$$\frac{\bar{D}_{m,i+1}}{D_{eq,m}} = \frac{[\bar{D}_{m,i+1}]_Z - (D_{eq,m} - [\bar{D}_{m,i+1}]_m)}{D_{eq,m}} + 1 \quad (29)$$

Eq. (14) is now compared with eq. (29). By multiplying the first term of eq. (14) (eq. 27) with a factor $D_{eq,L}/D_{eq,m}$ the following relation, eq. (30) is obtained

$$(\bar{M}'_i - \bar{M}'_{i+1}) \cdot \frac{\bar{T}}{\bar{M}_{eq} \cdot \Delta t} \cdot \frac{D_{eq,L}}{D_{eq,m}} + 1 = \frac{[\bar{\epsilon}_i]_Z - [\bar{\epsilon}_{i+1}]_Z - \Delta \bar{\epsilon}}{D_{eq,m} \cdot A \cdot \Delta t} + 1 \quad (30)$$

In the case where the detector has the same radiation absorption and electron scattering properties as mylar it is obvious that

$$[\bar{D}_{m,i+1}]_Z = \frac{1}{A \cdot \Delta t} ([\bar{\epsilon}_i]_Z - [\bar{\epsilon}_{i+1}]_Z) \quad (31)$$

and

$$D_{eq,m} - [\bar{D}_{m,i+1}]_m = \frac{\Delta \bar{\epsilon}}{A \cdot \Delta t} \quad (32)$$

With a LiF-teflon detector, however, there exists a discrepancy between the two sides in both eqs (31) and (32), contributing to give a deviation between the quantities in the eqs (29) and (30).

As LiF-teflon scatters back the electrons more effectively than mylar the absorbed energy in a LiF-teflon detector from the electrons generated in the metal foil is less than the absorbed energy from these electrons in a thick layer of mylar at the same location. With a LiF-teflon detector the right hand side of eq. (31) is therefore considered to give an underestimate of $[\bar{D}_{m,i+1}]_Z$, the degree of which depends on i as well as on Z (see Appendix). $[\bar{D}_{m,1}]_Z$ is underestimated by about 3 per cent when $Z=13$ (Al) but by less than 2 per cent when $Z \geq 29$ (Cu, Sn, or Pb). For large values of i , scattering of electrons between the detector and the metal foil can be neglected and the underestimate is about 3 per cent independent of Z .

It is more difficult to estimate the discrepancy between the two sides in eq. (32) than in eq. (31). When $Z \geq 29$ (Cu, Sn, or Pb) or for values of $i > 1$ independent of Z , the term $(D_{eq,m} - [\bar{D}_{m,i+1}]_m)$ gives, however, a negligible contribution to eq. (29), so that in these cases the discrepancy between the two sides in eq. (32) is of minor importance. (As in mylar most of the secondary electrons are Compton electrons with shorter ranges than photoelectrons $[\bar{D}_{m,i+1}]_m \simeq D_{eq,m}$ for $i > 1$.) Thus, when $Z \geq 29$ (Cu, Sn, or Pb) or for values of $i > 1$ the main deviation between the quantities in the eqs (29) and (30) is due to the underestimate of $[\bar{D}_{m,i+1}]_Z$ (eq. 31), the deviation being less than 3 per cent.

With Al and $i=0$ or 1 the contribution of the term $(D_{eq,m} - [\bar{D}_{m,i+1}]_m)$ to eq. (29) is not negligible but can be estimated to be < 15 per cent. At 200 kV and $i=0$ the contribution is about 15 per cent. Similarly as in the Appendix it can be shown that for $i=0$ the quantity $\frac{\Delta \bar{\varepsilon}}{A \cdot \Delta t}$ (eq. 26) underestimates $(D_{eq,m} - [\bar{D}_{m,1}]_m)$, an underestimate which is less than 20 per cent. In this case the underestimate of $(D_{eq,m} - [\bar{D}_{m,1}]_m)$ is compensated by the underestimate of $[\bar{D}_{m,1}]_{Al}$ (eq. 31), so that the deviation between the quantities in eqs (29) and (30) is again less than 3 per cent.

Relative depth doses in soft tissue. From a radiologic point of view it would be of greater interest to convert the results to yield relative depth doses in soft tissue. This is a more difficult task. The mass stopping power of mylar is 7 per cent lower than the mass stopping power of soft tissue (Fig. 7). For this reason, the absorbed dose in soft tissue at a point close to the interface is higher and the depth doses in soft tissue are steeper than in mylar. By averaging the absorbed dose over a thickness $\Delta t = 0.486$ mg/cm², the following relation is supposed to be valid to better than 7 per cent

$$[\bar{D}_{m,1}]_Z \simeq [\bar{D}_{s,\Delta t}]_Z \quad (33)$$

Here $[\bar{D}_{s,\Delta t}]_Z$ is the mean absorbed dose from electrons generated in a metal foil in a $\Delta t = 0.486$ mg/cm² thick layer of soft tissue close to the metal foil.

An approximate solution of the total relative mean absorbed dose in a $\Delta t = 0.486$ mg/cm² thick layer of soft tissue close to the metal foil is given by eq. (14) when the first term of eq. (14) is multiplied with a factor $D_{eq,L}/D_{eq,s}$.

$$\frac{\bar{D}_{s,\Delta t}}{D_{eq,s}} \simeq (\bar{M}'_0 - \bar{M}'_1) \cdot \frac{\bar{T}}{\bar{M}_{eq} \cdot \Delta t} \cdot \frac{D_{eq,L}}{D_{eq,s}} + 1 \quad (34)$$

Here $D_{eq,s}$ is the electronic equilibrium absorbed dose in soft tissue. The relation in eq. (34) is probably valid to within 10 per cent, the approximation being better the more the dose contribution from the electrons generated in the metal foil, $[\bar{D}_{s,\Delta t}]_Z$, dominates in the total absorbed dose, $\bar{D}_{s,\Delta t}$.

Precision of the measurements

A complete set of $\bar{M}'_i$ -signals was, for each radiation quality, measured twice with Pb, Sn and Cu, and 4 times with Al. Each time three $\bar{M}'_0$ - and three $\bar{M}'_1$ -signals were determined. The remaining statistical uncertainty, given as a 90 per cent confidence interval, in the results obtained by using $\bar{M}'_0 - \bar{M}'_1$ with eq. (14)

is then for 100 kV: Al 12 per cent, Cu 7 per cent, Sn 7 per cent, Pb 4 per cent and for 200 kV: Al 15 per cent, Cu 8 per cent, Sn 6 per cent, Pb 4 per cent. For increasing values of i the relative statistical uncertainty in the difference of the signals $\overline{M}'_i - \overline{M}'_{i+1}$ increases to at the most 50 per cent. Due to the increasing relative importance of the constant in the second term of eq. (14) this corresponds to a statistical uncertainty of at most 20 per cent in the results obtained with eq. (14).

RESULTS

Depth doses beyond the transition region

Metal foil at phantom surface

The results are given in Fig. 8. In each diagram the upper solid curve shows the depth doses obtained before the metal foils are inserted into the beam, the lower solid curve the depth doses obtained with any one of the indicated metal foils raised 21 cm above the surface of the phantom. (In fact the absolute position of the lower solid curve varied somewhat with the metal foil used. The curve drawn shows a mean position such that the actual positions were all within 1.5 per cent of the mean position represented.) The other curves give the depth doses with the indicated metal foils on the surface of the phantom. Due to the collimation of the beam, the lower solid curve can be interpreted as the depth doses caused by the transmitted primary photons and photons scattered within the phantom.

The effect of the K-edge of Sn on the spectrum of transmitted primary photons with 100 kV (Fig. 3a) is reflected in the somewhat steeper depth doses obtained with the raised Sn-foil than with raised Al-, Cu-, or Pb-foil (Figs 8a, b). The low energy photons, < 29 keV, transmitted through the window below the K-edge of Sn, are rapidly absorbed due to photoelectric absorptions, the dominant interaction process at energies below 30 keV in $(C_2F_4)_n$. No such effect is caused by the K-edge of Pb with 200 kV (Fig. 3b) since in the energy region around 88 keV the interaction cross section in $(C_2F_4)_n$ varies only slowly with photon energy. With both 100 kV and 200 kV the reduction in the absorbed dose at the phantom surface caused by the introduction of the raised metal foils agrees very well, within ± 3 per cent, with the dose reduction calculated taking into account only the primary photons. This indicates that the variation of the absorbed dose backscatter factor is slow when the primary radiation quality is changed by the filtering effect of the metal foils. This is in accordance with the slow variation of the energy albedo with the spectrum of roentgen radiation (CARLSSON 1963).

With the metal foils close to the phantom surface an additional contribution to the depth doses from secondary photons is obtained.

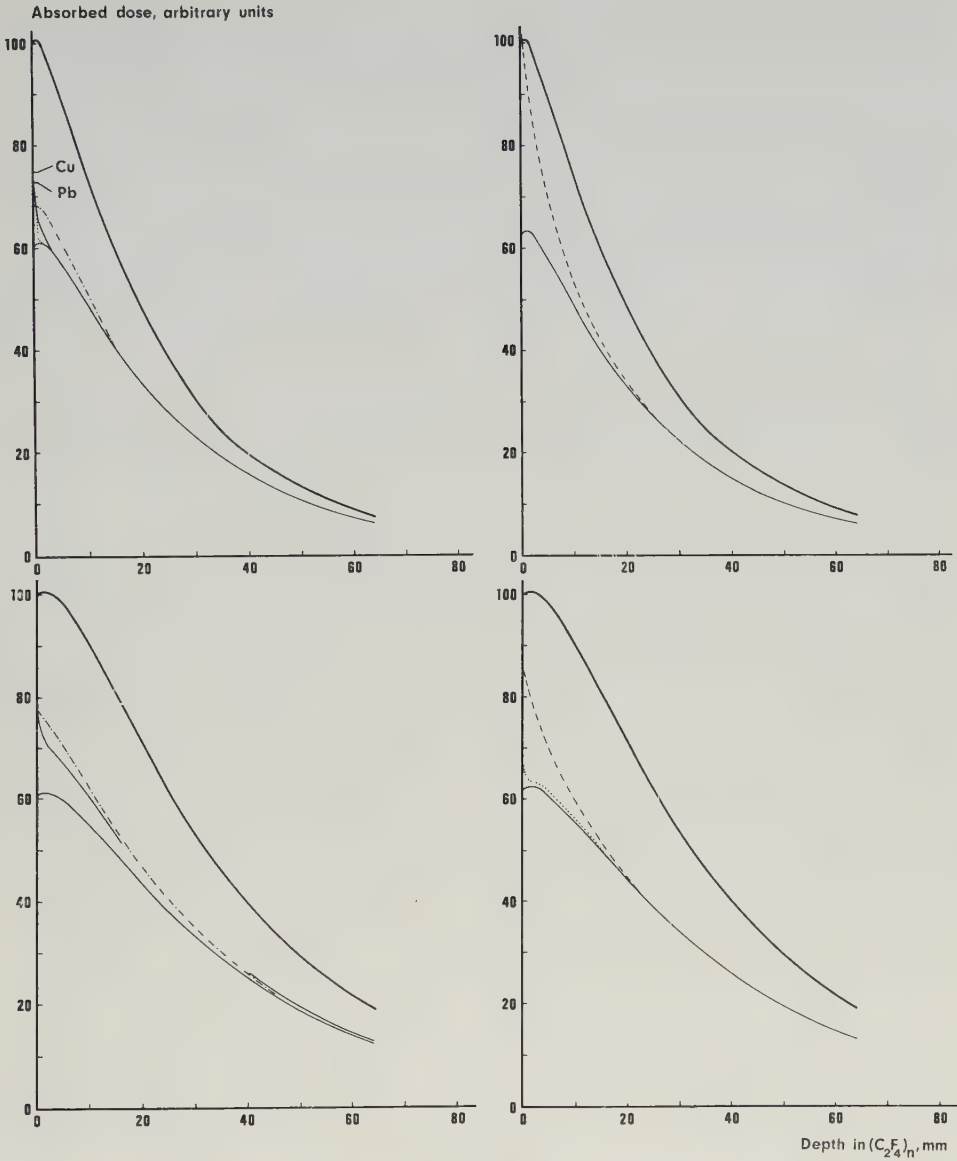


Fig. 8. Depth doses in teflon beyond the transition region. The upper solid curves give the depth doses with a beam of primary photons of 100 kV (a, top left and b, top right) and 200 kV (c, bottom left and d, bottom right). The lower solid curves give the corresponding depth doses with the primary photons additionally filtered by metal foils of a) Pb, Cu, Al b) Sn c) Pb, Al and d) Sn, Cu. The other curves give the depth doses with the indicated metal foils on the surface of the phantom: — Pb, --- Sn, Cu, -.-.- Al.

With 100 kV and Cu, Sn, or Pb (Figs 8a, b) the additional dose contribution is due to the fluorescence radiation emitted following photoelectric absorption, in all cases the predominant interaction process. The mean free path in $(C_2F_4)_n$ is for the K-fluorescence photons of Cu ($\bar{E}_K = 8.14$ keV, BERGER 1961) $\simeq 0.4$ mm, for the L-fluorescence photons of Pb ($\bar{E}_L = 11.67$ keV, BERGER) $\simeq 1.1$ mm, and for the K-fluorescence photons of Sn ($\bar{E}_K = 25.78$ keV, WAPSTRA et coll. 1959) $\simeq 9.7$ mm. The isotropy of the fluorescence photons increases the steepness of the dose gradients. The much greater fluence of fluorescence photons at the phantom surface with Sn than with Cu or Pb is due to a higher fluorescence yield, $\omega_K(\text{Sn}) = 0.84$, $\omega_K(\text{Cu}) = 0.41$, $\omega_L(\text{Pb}) = 0.39$ (FINK et coll. 1966), and a larger mean free path of the fluorescence photons of Sn in the metal itself. All the metal foils are about equally thick compared to the mean free paths of the primary photons so that the number of primary interaction processes is approximately the same in all foils. However, while the thickness of the Sn-foil is equal to one third of the mean free path of the K-fluorescence photons, $\frac{1}{\mu_{\text{Sn}}} (25.78$ keV) $= 0.14$ mm, the thickness of the Cu- and Pb-foils are about 4 and 3 times the mean free paths of the K-fluorescence photons of Cu and of the L-fluorescence photons of Pb, respectively, $\frac{1}{\mu_{\text{Cu}}} (8.14 \text{ keV}) = 0.024$ mm and $\frac{1}{\mu_{\text{Pb}}} (11.67$ keV) $= 0.011$ mm. Thus, a larger fraction of the emitted fluorescence photons escape from the Sn-foil than from the Cu- or Pb-foils. The escape of the K-fluorescence photons of Cu and L-fluorescence photons of Pb is, however, clearly verified. (The relative dose contributions from the K-radiation of Cu and the L-radiation of Pb may be somewhat underestimated due to a lower efficiency of the detectors for these low energy photons than for the primary photons, TOCHILIN et coll. 1968.) In absorbed dose measurements the detection of the lower energy fluorescence photons is favoured by a high energy absorption in LiF per photon. The absorbed dose in LiF per incident photon is about 15 times higher for the K-fluorescence photons of Cu than for the K-fluorescence photons of Sn and about 35 times higher than for the average of the primary photons. For this reason dose distribution measurements with high spatial resolution can be of value to determine the fluence of low energy photons in the presence of photons of higher energy.

With 200 kV and Sn (Fig. 8d) the additional dose contribution is still mainly due to the K-fluorescence radiation as can be seen from the characteristic dose gradient. The K-fluorescence photons are generated by the photoelectric absorption of primary photons as well as the photoelectric reabsorption of Compton scattered photons. The absorbed dose at the surface from the K-radiation relative to the absorbed dose from the primary photons is a factor of 1.7 smaller

with 200 kV than with 100 kV radiation. The absorbed dose in LiF per incident primary photon is somewhat less with 200 kV than with 100 kV radiation so that the fluence of K-fluorescence photons at the phantom surface per transmitted primary photon is about a factor of 2 less with 200 kV than with 100 kV radiation. This is due to the fact that at 200 kV the K-fluorescence photons are emitted from a foil which is five times thicker than at 100 kV and hence a smaller fraction of the fluorescence photons emitted can escape. Per transmitted primary photon even more photoelectric absorptions in the K-shell of Sn occur in the thicker foil. The absorbed dose in LiF from the primary photons is reduced by the same factor for each of the foils but, because of the energy distribution of the primary photons, the reduction in the number of primary photons is less with 100 kV than with 200 kV radiation. With 200 kV radiation a larger fraction of the primary interaction processes is due to Compton scattering while with 100 kV radiation not all of the primary photons are energetic enough to interact photoelectrically with the K-electrons of Sn.

With 200 kV and Cu (Fig. 8d) a dose contribution from the K-fluorescence photons of Cu can still be detected. The reduction in the fluence of K-fluorescence photons per transmitted primary photon arises partly because of the thicker Cu-foil at 200 kV, the same effect as discussed above with Sn, and partly since for photon energies above 100 keV a considerable fraction, > 0.30 , of the interaction processes is due to Compton scattering. In addition to the dose contribution from the K-fluorescence photons, a dose contribution from Compton scattered photons is seen.

With 200 kV and Pb (Fig. 8c) dose contributions from K- and L-fluorescence photons can be distinguished. Photoelectric absorption is also with 200 kV radiation the predominant interaction process in Pb. L-fluorescence photons are emitted subsequent to photoelectric absorption in the L-shell as well as in the K-shell. Photoelectric absorption in the K-shell is almost as effective in generating L-fluorescence photons as that in the L-shell. The probabilities for the emission of a L-fluorescence photon are 0.32 and 0.39, respectively (FINK et coll. 1966, ROBINSON & FINK 1960).

With Al the additional dose contribution is, for both radiation qualities (Fig. 8a, c) from Compton scattered photons only. Although photoelectric processes occur in Al, the fluorescence yield is low, $\omega_K=0.04$ (FINK et coll.), as is the energy of the fluorescence photons, $E_K=1.49$ keV (BERGER 1961), so that these are mainly absorbed within the transition region. This is also the case with the L-, M-, etc. fluorescence photons from Sn and Cu and with the M-, N-, etc. fluorescence photons from Pb. The mean free path in $(C_2F_4)_n$ for a 4 keV photon is 9.7 mg/cm^2 corresponding to the range of a 90 keV electron.

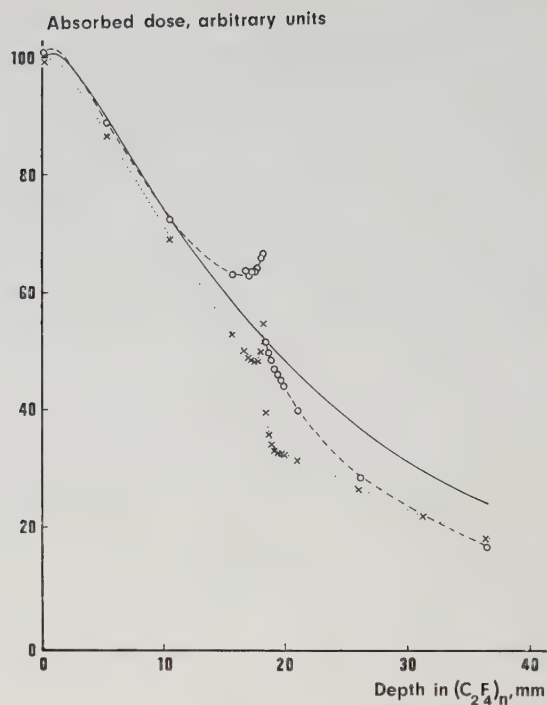


Fig. 9. Depth doses in teflon obtained with 100 kV roentgen rays with metal foils of Sn (-----) and Cu (.....) inserted 18 mm below the phantom surface. The solid curve shows the depth doses within a homogeneous (undisturbed) phantom.

Metal foil inserted in the phantom

Results obtained at 100 kV with the Sn- or the Cu-foil inserted in the phantom are given in Fig. 9. The solid curve represents the (undisturbed) depth doses before the insertion of the metal foils, the other curves the depth doses with the metal foils at a depth of 18 mm below the phantom surface (Fig. 2, position c).

Behind the metal foils the depth doses are reduced due to the higher attenuation of the primary photons in the metal foils than in the same thickness (on a linear scale) of teflon. With the metal foils on the phantom surface the absorbed dose from the primary photons was reduced by the same factor behind both foils. Due to the change in the energy distribution of the impinging primary photons, caused by the filtering in 18 mm of teflon, the absorbed dose from the primary photons is smaller behind the Sn-foil than behind the Cu-foil. This effect can be anticipated from the observation that the depth doses are steeper behind the raised Sn-foil than behind the raised Cu-foil (Fig. 8a, b). The spectrum of primary photons incident on the foils at 18 mm depth contains relatively

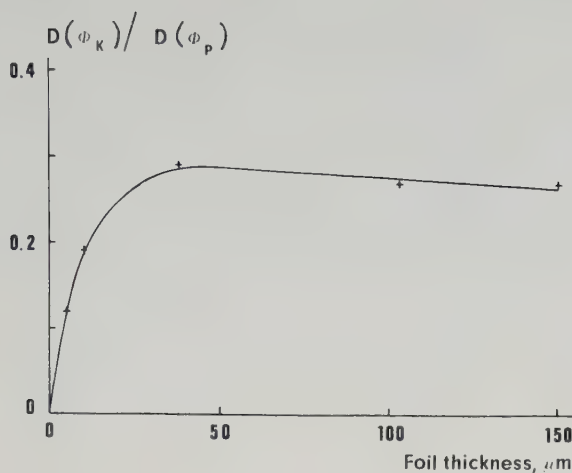


Fig. 10. Absorbed dose at the phantom surface from the K-radiation of Cu relative to that from the transmitted primary photons as a function of the thickness of Cu-foil. Irradiation with 100 kV roentgen rays.

fewer primary photons with energies < 29 keV which can be transmitted through the K-edge window of Sn.

Due to the isotropic emission of the fluorescence photons, a contribution to the depth doses from the K-radiation of Sn and Cu is seen on both sides of the metal foils. In front of the Cu-foil, outside the region of influence of the K-radiation, the depth doses are reduced due to the lack of backscattered Compton photons. The lack of backscattered Compton photons in front of the Sn-foil is compensated for by the contribution from the K-fluorescence photons.

*Relative dose contribution from the K-radiation of Cu
as a function of foil thickness*

Cu-foils of varying thickness, ranging from 5 μm to 150 μm , were placed at positions (a) and (b) in Fig. 2 and irradiated with 100 kV roentgen rays. The absorbed dose at the phantom surface from the K-radiation of Cu relative to that from the transmitted primary photons (and from the photons backscattered by the phantom) was estimated. The results are given in Fig. 10.

The relative dose contribution from the K-radiation of Cu reaches a maximum when the foil thickness is about twice the mean free path of the K-fluorescence photons in Cu, which is $\simeq 24$ μm . The range of a 100 keV electron, the energy of the most energetic secondary electrons, is $\simeq 25$ μm in Cu. Thus a considerable fraction of the absorbed dose in LiF from the K-radiation is due to those K-fluorescence photons generated within the transition region in Cu.

With monoenergetic primary photons the fluence of K-fluorescence photons at the phantom surface per transmitted primary photon is expected to increase steadily with increasing foil thickness. Here, from Fig. 10 and the fact that the

absorbed dose in LiF per transmitted primary photon decreases somewhat with increasing foil thickness due to the change in the energy distribution of the transmitted photons, the fluence of K-fluorescence photons per transmitted primary photon seems to reach a maximum value and to decrease slowly with increasing foil thicknesses $> 50 \mu\text{m}$. This must also be an effect of the change in the energy distribution of the transmitted primary photons with increasing foil thickness. Per transmitted primary photon the number of photoelectric absorptions per unit length of the Cu-foil close to the phantom surface decreases with increasing foil thickness.

In Cu the mean free path of the K-fluorescence photons is, as was pointed out above, approximately equal to the range of the most energetic secondary electrons. In teflon, however, the mean free path of the K-fluorescence photons, $\approx 400 \mu\text{m}$, is about five times larger than the range (c.s.d.a.) of a 100 keV electron, $\approx 82 \mu\text{m}$.

Depth doses within the transition region

The results are given in Fig. 11 for 100 kV and 200 kV, respectively. The continuous curves are fitted to the histograms obtained experimentally. The dose gradients are mainly caused by the photoelectrons generated in the metal foils. There is also a contribution from Auger electrons, which, however, are mostly of such low energies that they only contribute to the mean absorbed dose in the first mylar film. This is also the case with certain groups of photoelectrons. The presence of the K-edges of Sn and Pb in the spectra of the primary radiation at 100 kV and 200 kV, respectively, results in the emission of low energy K-electrons from Sn and Pb. One result of this is seen especially well at 100 kV where the dose gradient with Sn is evidently steeper than the dose gradient with Cu (Fig. 11a).

The experimental results have been converted to give dose enhancement factors in soft tissue averaged over a 0.486 mg/cm^2 thick layer close to the metal foils in Fig. 12. This conversion of the experimental results, eq. (14) (Fig. 11), was performed according to eq. (34). In calculating the correction factor $D_{\text{eq,L}}/D_{\text{eq,s}}$, full account was taken of the photon radiation spectrum. The absorbed dose backscatter factor, $(B_D)_{\text{LiF}}$, of the primary radiation transmitted through the metal foils was experimentally determined to be 1.14 with radiation of 100 kV and 1.17 with radiation of 200 kV. The spectral distribution of the backscattered primary radiation was assumed to be the same as in a water phantom and was calculated from data given by HETTINGER (1960). Furthermore, the extra dose contribution in LiF from the secondary photon radiation obtained with the metal foils on the phantom surface was determined from Fig. 8. The

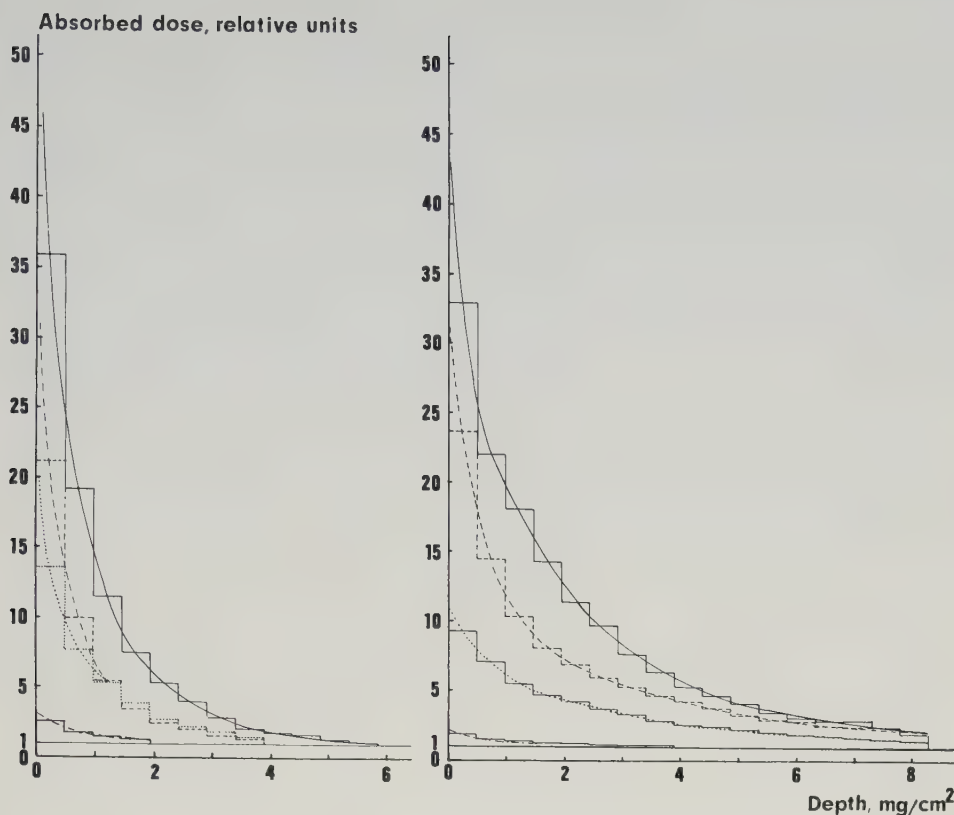


Fig. 11. a) and b) Depth doses in mylar from photoelectrons generated in an adjacent metal foil of Pb (—), Sn (----), Cu (.....), and Al (-·-·-), irradiated with a roentgen beam of 100 kV (a, left) and 200 kV (b, right). The depth doses are normalized to the electronic equilibrium absorbed dose in LiF. The continuous curves are fitted to the histograms obtained experimentally.

spectral distribution of the secondary photon radiation obtained with Al on the surface was estimated approximately. From data given by HETTINGER & STARFELT (1959), HETTINGER (1960), and BJÄRNGARD & HETTINGER (1961), the spectra of the secondary photons transmitted through a water layer (of the same thickness, in mass per unit area, as the Al-foil) and of the additional secondary photons generated by bringing the water layer in contact with an underlying water phantom were estimated. These spectra were modified to the case of an Al-layer at the phantom surface by taking into account the differences in the spectra of scattered photons within Al- and water phantoms given by BRUCE & JOHNS (1960). With Pb and 200 kV the backscattering of the K-radiation from

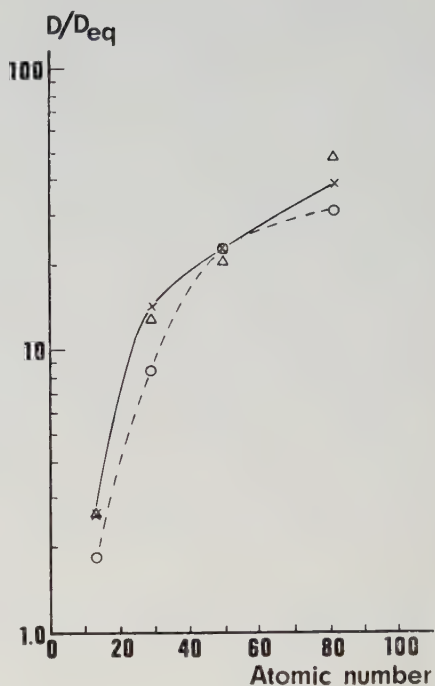


Fig. 12. Dose enhancement factors, $\bar{D}/D_{eq}$, in soft tissue averaged over a 0.486 mg/cm^2 thick layer close to metal foils of Pb, Sn, Cu and Al, irradiated with primary photons generated at 100 kV ($\times$ — $\times$) and 200 kV (o---o) potential. Experimental results of KRAMER (1966) obtained with 60 kV roentgen rays and with exoelectron emitting dosimeters of BeO are included (Δ).

the phantom was estimated using the backscatter factor of the primary radiation corrected for the change due to the isotropic incidence of the K-radiation on the phantom surface (BERGER & RASO 1960). With Cu and 200 kV the spectral distribution of the Compton scattered photons was assumed to be the same as that of the transmitted primary photons. This crude approximation is motivated by the small relative dose contribution from these photons. In all other cases, the secondary radiation was assumed to consist exclusively of monoenergetic fluorescence photons. The energy of the fluorescence photons was assumed to be equal to the mean energy of the fluorescence photons belonging to the same series weighted according to their relative frequencies. Values of the mean energies were taken from WAPSTRA et coll. (1959), and BERGER (1961).

For all the materials investigated with the exception of Sn, the average dose enhancement factor is, though slowly varying, lower at 200 kV than at 100 kV (Fig. 12). Because of the sharp dose gradient with Sn at 100 kV, due to the K-edge of Sn, the average dose enhancement factor is relatively low in this case. In fact, it is not possible to represent the dose enhancement factor as a continuously varying function of the atomic number as long as photoelectric absorption edges are present in the spectrum of the primary photons. The curves in

Fig. 12 have been drawn in order to facilitate the survey of the results and should not be taken as strictly representing the Z-dependence.

In Fig. 12 the experimental results of KRAMER (1966) obtained with exoelectron emitting detectors of BeO and 60 kV roentgen rays are included. KRAMER gives the exoelectron emission as a function of the atomic number of a backing material of 2 mm thickness. Here (Fig. 12) his results have been normalized to 1 for the case of BeO as backing material. Thus, the 'dose enhancement factors' of KRAMER are normalized differently from those presented in this investigation, i.e. to the electronic equilibrium absorbed dose in the photon fluence existing with BeO as backing material instead of to the electronic equilibrium absorbed dose in the actual photon fluence, so that, even though BeO is approximately equivalent to soft tissue, the results are not directly comparable. Furthermore, the effective thickness of the BeO-detector is much less than 0.486 mg/cm^2 . On the other hand, in the measurements of KRAMER the detector was situated at a 'short distance' from the backing material. In a case where the dose gradient is very steep, even a small air gap, 1 mm of air $\simeq 0.13 \text{ mg/cm}^2$, has considerable influence upon the results and the dose gradients are steeper with 60 kV than with 100 kV. Another unknown parameter in the measurements by KRAMER is the cleanness of the metal surface. In the present measurements the metal surface was repeatedly polished to avoid oxide layers.

DISCUSSION

Comparison of the results in the transition region with existing theories

Dose distributions at plane Al-mylar and Pb-mylar interfaces Measurements and simplified theory

It was pointed out above that there may exist a systematic error in the measurements of the dose distributions within the transition region due to a possible discrepancy between the weighted mean efficiency of the surface layers, η'_0 , and the mean efficiency over all depths of the detectors, η . By comparing the experimental results in the transition region with calculated dose distributions, the question of an eventual discrepancy between the efficiencies η'_0 and η can be clarified. Al and Pb were chosen for the comparison, the theory by HOWARTH (1965) being used for the calculations. In the case of Pb, his theory was modified using the developments for high Z interfaces outlined by ASPIN & JOHNS (1963) and CHARLTON (1970). By choosing such different Z as Al and Pb in the comparison, the limitation of this simplified theory with regard to the atomic number of the adjacent material is illustrated. As the experimental results, eq. (14), are most easily converted to yield dose enhancement factors in mylar, eq. (30), dose distributions in mylar were calculated. In the calculations and conversion of the experimental results, full account was taken of the photon radiation spectrum (with the approximations about the spectral distributions of the backscattered and secondary photons from the Al-foils mentioned above). The calculations were performed assuming the emission of monoenergetic photoelectrons (K-electrons) from Al and mylar, while in the case of Pb the photoelectrons were assumed to be of three different energies: $h\nu = 88$ keV (K-electrons), $h\nu = 15$ keV (L-electrons), and $h\nu = 2.5$ keV ($M+N+\dots$ -electrons). In all cases the energy transferred to Auger electrons was taken into consideration. The Auger electrons from Al and mylar were assumed to be of such low energies (< 1.5 keV) that they are totally absorbed within a distance < 0.05 mg/cm² from the interface (ICRU 1970). The following simplifying assumptions were made about the energies of the Auger electrons from Pb: in filling a K-shell (L-shell) vacancy two vacancies in the L-shell (M-shell) are created, i.e. the energy of an Auger electron emitted in filling a K-shell (L-shell)

vacancy $\simeq 58$ keV ($\simeq 9$ keV). In filling a vacancy in shells higher than the L-shell, the Auger electrons emitted are of energies < 4 keV and were assumed to be absorbed within a distance < 0.05 mg/cm² in mylar (ICRU 1970).

The ratio between the stopping powers of lead and mylar varies markedly with electron energy. At 200 keV the ratio is a factor 1.4 higher than at 10 keV. As was pointed out above, assumption (3) about the ratio between the straight line ranges of the electrons in lead and mylar gives the ratio between the calculated absorbed dose in a small cavity of mylar within lead and the absorbed dose in the lead. As a consequence of assumptions (1) and (2), the calculated absorbed dose in mylar close to a plane interface from electrons generated in lead is equal to half the calculated absorbed dose in a small cavity of mylar within the lead. A version of assumption (3) slightly modified from those given by ASPIN & JOHNS (1963) and CHARLTON (1970) was adopted here. The ratio between the straight line ranges was assumed to be equal to the inverse ratio of the stopping powers of an appropriate electron energy between the starting energy and zero energy, so that close to the plane interface the calculated absorbed dose in mylar from electrons generated in lead is equal to half of the Bragg-Gray-Laurence dose (NCRP 1961) in mylar within lead. Values of the stopping powers were taken from BERGER & SELTZER (1964). As there are no tabulated values for electron energies below 10 keV an extrapolation of the stopping power ratio down to zero energy was used.

The absorbed dose in a small cavity within lead varies somewhat with the cavity size due to the effect of δ -rays, an effect which is included in the cavity ionization theory by SPENCER & ATTIX (1955). As no calculations of the Spencer-Attix type are available for low energy roentgen rays and as the δ -ray correction is supposed to be small in this case (NCRP 1961), the use of the Bragg-Gray-Laurence method is well motivated.

The tabulated values (HUBBELL 1969) of the mass energy absorption coefficient for lead were corrected for neglect of the escape of L-fluorescence photons emitted following photoelectric absorption in the K-shell (ALM CARLSSON 1971). Dose enhancement factors, D/D_{eq} , were calculated for monoenergetic photons among them those with the energies of K- and L-fluorescence photons. The dose enhancement factor for a spectrum of photon energies is obtained as a weighted mean of the dose enhancement factors for monoenergetic photons with the electronic equilibrium absorbed dose in mylar as a weighing factor. In calculating this weighted mean, the sum of the fluences of the K- and L-fluorescence photons (estimated from Fig. 8a, c) was added to the spectrum of primary and Compton scattered photons. The energy emitted as M-, N-, etc. fluorescence radiation was assumed to be absorbed in the same way as the secondary electrons.

In the calculations of the dose enhancement factors for monoenergetic photons, it is implied that on both sides of the interface the photon fluence is approximately constant over depths equal to the range of the most energetic secondary electrons, i.e. $\frac{1}{\mu} \gg R$.

This condition is also required for electronic equilibrium outside the transition region. With high Z materials and low energy photons, it can be questioned if this condition is satisfied. HUBBELL (1969) gives the quotient between the electron range (c.s.d.a.) and the photon mean free path as a function of the energy. In lead this quotient is 0.11, 0.17 and 0.053 at 10, 100 and 1000 keV, respectively, while in a low Z material, such as water, the corresponding values are 0.0012, 0.0023 and 0.030 increasing to 0.11 at 10 MeV. The quotients given by HUBBELL are valid when the photon and electron have the same energy. Most of the secondary electrons generated by a low energy photon in a high Z material are, however, of lower energy than the photon. For example, with 100 keV photons the quotient between the range (c.s.d.a.) of the K-electrons (L-electrons) and the mean free path of the photons is ≈ 0.006 (≈ 0.12). The high Rutherford scattering of electrons in a high Z material means that the actual penetration depth of the electrons in a high Z material is smaller than the full rectified range (c.s.d.a.). Rutherford scattering also increases the isotropy of the electrons. The combination of the energy spectrum and scattering of electrons is such that electronic equilibrium is a better approximation than the quotients by HUBBELL appear to indicate.

In calculating the weighted mean of the dose enhancement factors, D/D_{eq} , for monoenergetic photons as described above, it is assumed that the photon fluence is approximately constant throughout the transition region in mylar, for photons of all energies occurring in the spectrum. With a spectrum of photon energies, the transition region is defined by the range of the most energetic secondary electrons generated by the photons in the spectrum. The mean free path of the L-fluorescence photons of Pb in mylar is ≈ 370 mg/cm² while the range (c.s.d.a.) of a 200 keV electron is ≈ 48 mg/cm², i.e. the mean free path of the L-fluorescence photons is about eight times the range of the most energetic secondary electrons with the 200 kV roentgen radiation. In practice, however, the transition region in mylar at 200 kV is only about 10 mg/cm² (Fig. 11b). The fluence of L-fluorescence photons at the interface was estimated from Fig. 8c. In that measurement 16 mg/cm² of mylar was interposed between the detector and the metal foil. As the mean free path of the L-fluorescence photons is about 40 times the extension of the practical transition region (Fig. 11b), the attenuation of the L-fluorescence photons in this region has been neglected.

The results of the measurements, after appropriate correction with eq. (30), are compared with the calculated values in Fig. 13 for Al and Fig. 14 for Pb. The dotted curves represent the calculated relative dose distributions. The solid curves are fitted to the histograms obtained experimentally.

With Al (Fig. 13) there is for both radiation qualities as good an agreement between the calculated and measured dose distributions as has, at equivalent interfaces, been obtained by other investigators (cf. the results of WINGATE et coll. 1962).

With Pb (Fig. 14) the calculated absorbed dose close to the interface is roughly a factor of 2 higher than the measured absorbed dose. At 100 kV (200 kV) the

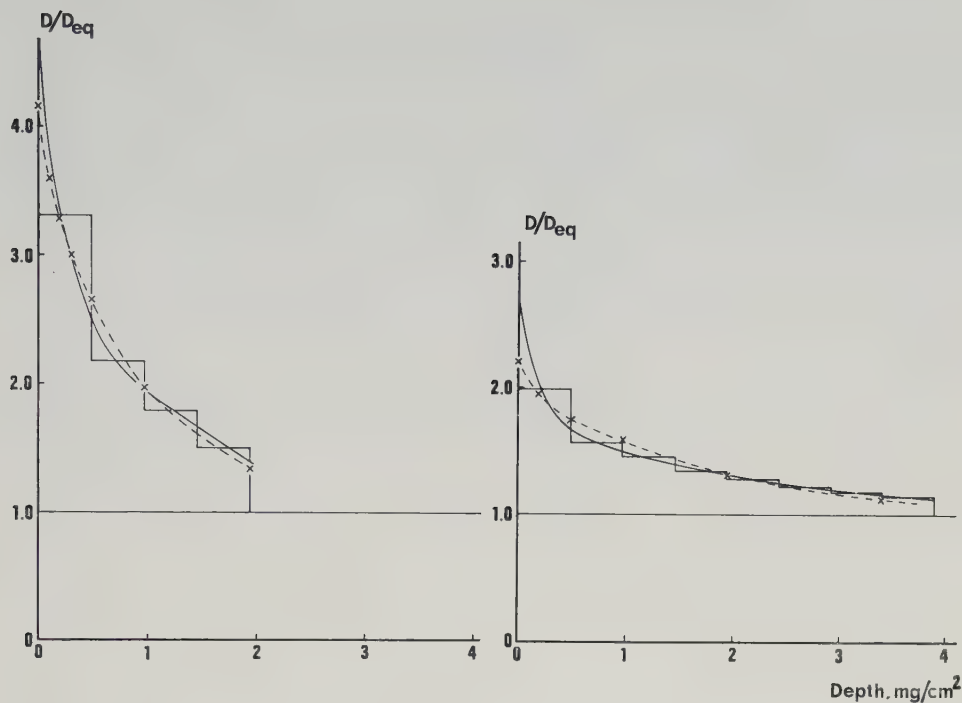


Fig. 13. a) and b) Calculated ($\times$ — — — $\times$) and experimentally determined (—) relative dose distributions, D/D_{eq} , in mylar adjacent to a plane metal foil of Al, irradiated with a roentgen beam of 100 kV (a, left) and 200 kV (b, right). The solid curves are fitted to the histograms obtained experimentally.

calculated absorbed dose is a factor of 2.3 (2.0) higher than the 'measured' absorbed dose as given by an extrapolation of the solid curves to zero depth. The calculated mean absorbed dose in the first mylar film is at 100 kV (200 kV) a factor of 1.9 (2.0) higher than the measured mean absorbed dose in the first mylar film. As discussed earlier the applied theory is likely to overestimate the absorbed dose close to the plane interface for a material of such high Z as Pb. By using an analyzing method introduced by DUTREIX & BERNARD (1965), an attempt was made to determine the degree of overestimate quantitatively.

Effects of electron multiple scattering

Dutreix formula. Consider a very thin layer of mylar between two slabs of a medium Z , thick enough to give electronic equilibrium. D_Z^F is the absorbed

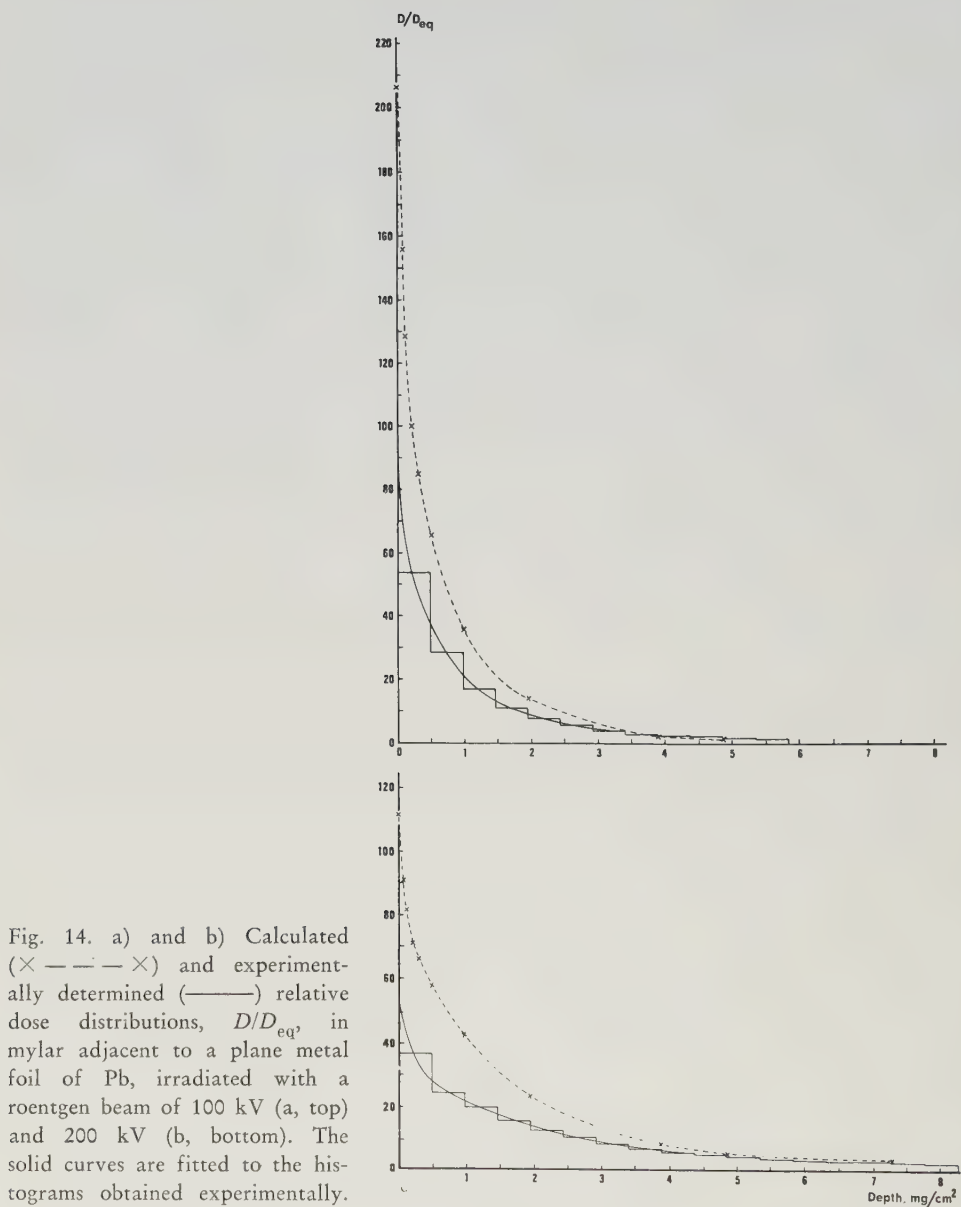


Fig. 14. a) and b) Calculated ($\times$ — — — $\times$) and experimentally determined (—) relative dose distributions, D/D_{eq} , in mylar adjacent to a plane metal foil of Pb, irradiated with a roentgen beam of 100 kV (a, top) and 200 kV (b, bottom). The solid curves are fitted to the histograms obtained experimentally.

dose in the mylar layer from the electrons generated in front of it which traverse it for the first time and D_Z^B is the corresponding absorbed dose from electrons generated behind it. The total absorbed dose, D_{ZZ} , in the mylar is

$$D_{ZZ} = \frac{D_Z^F + D_Z^B}{1 - b_Z} \quad (35)$$

where b_Z is the absorbed dose backscatter coefficient of the medium Z . Replacing the slab at the back with a slab of a medium X of lower atomic number, the absorbed dose in the mylar from electrons generated in the medium Z , D_{ZX} , is given by

$$D_{ZX} = \frac{D_Z^F (1 + b_X)}{1 - b_X \cdot b_Z} \quad (36)$$

Here b_X is the absorbed dose backscatter coefficient of the medium X .

For low energy photons and a high Z material such as Pb, it is a reasonable approximation to write

$$D_Z^F \simeq D_Z^B \quad (37)$$

Because Rutherford scattering of the electrons increases strongly with increase in the atomic number of the absorber the absorbed dose at a plane interface from electrons generated in an adjacent high Z material is, even for high energy photons, relatively independent of the beam direction (HINE 1951, DUTREIX & BERNARD 1965). With ^{60}Co gamma radiation DUTREIX & BERNARD obtained $D_{\text{Pb}}^F \simeq 1.4 D_{\text{Pb}}^B$. On the other hand for low energy photons D_{Pb}^F may be somewhat larger than D_{Pb}^B due to the attenuation of the photons over the range of the secondary electrons as discussed above.

Thus, half of the Bragg-Gray-Laurence dose in mylar under electronic equilibrium in Pb may be written

$$\frac{1}{2} \cdot D_{ZZ} \simeq \frac{D_Z^F}{1 - b_Z} \quad (38)$$

Thus, from eqs (36) and (38), the simplified theory overestimates the absorbed dose in mylar close to the interface from electrons generated in Pb by a factor of

$$\frac{\frac{1}{2} \cdot D_{ZZ}}{D_{ZX}} = \frac{1 - b_X \cdot b_Z}{(1 - b_Z)(1 + b_X)} \quad (39)$$

Since the dominant contribution to the total absorbed dose close to the interface comes from electrons generated in Pb (i.e. D_{ZX}), the total absorbed dose is approximately overestimated by the same factor, eq. (39). To solve eq. (39), knowledge of absorbed dose backscatter coefficients is necessary.

Backscattering of low energy electrons. A number of measurements of backscattering from solids for electrons with energies between 22 MeV and 1 keV have been carried out (BRAND 1936, BOTHE 1949, SELIGER 1952, STERNGLASS 1954, HOLLIDAY & STERNGLASS 1957, KANTER 1957, WRIGHT & TRUMP 1962, HARDER & FERBERT 1964, BISHOP 1966, and others). With low energy electrons < 500 keV the backscattering is almost independent of the electron energy. In high Z materials ($Z > 30$) there is, however, a decrease in the backscattering of electrons with energies < 5 keV (STERNGLASS 1954, HOLLIDAY & STERNGLASS 1957). This is due to the change from a strongly elastic or nuclear scattering to a predominantly inelastic or electron-electron scattering when the nuclear field is effectively screened by the atomic electrons.

Most of the measurements have been performed with perpendicularly incident electrons. An investigation by KANTER (1957) also measures the dependence of the backscattering on the angle of incidence. The degree of backscatter increases with the angle of incidence, the increase being more rapid the lower the atomic number of the scatterer. The Z -dependence of backscattering is thus less marked with isotropically incident electrons than with perpendicularly incident ones. The investigation by KANTER also involves measurements of the energy distribution of the backscattered electrons with the angle of incidence as a parameter.

Usually the results of electron backscattering measurements are expressed in terms of number albedoes, i.e. the ratio between the total number of backscattered electrons (with energies > 50 eV) and the total number of incident electrons. The absorbed dose backscatter coefficient is defined as the quotient between the absorbed dose from the backscattered electrons and that from the incident electrons. With a broad beam of incident electrons, i.e. with the beam diameter much larger than the range of the electrons, the absorbed dose backscatter coefficient can be calculated from a knowledge about the number albedo, the angular distribution and energy degradation of the backscattered electrons, and the electron stopping powers.

Choice of the appropriate backscatter coefficients for the Dutreix formula. In the present case, neither the angular distribution of the electrons emitted from the Pb-foil nor that of the backscattered electrons were known, so that only an approximate estimate of the absorbed dose backscatter coefficients of lead, b_Z , and mylar, b_X , could be made. The number albedo for an isotropic point electron source as given by KANTER (1957) was taken as a number fluence backscatter coefficient, i.e. the quotient between the fluences of backscattered and incident electrons. This choice is equivalent to presume that (a) electrons emitted from the Pb-foil have the same angular distribution as those from a plane isotropic electron source, and (b) the incident and backscattered electrons

have the same angular distributions. The backscattered electrons are energy degraded and the number fluence backscatter coefficient has to be corrected for the resulting increase in stopping power to yield the appropriate absorbed dose backscatter coefficient. The energy degradation was taken into account in terms of the mean energy loss of the backscattered electrons, calculated from data given by BISHOP (1967) and KANTER (1957). BISHOP gives the mean energy loss for perpendicularly incident electrons. The change in the mean energy loss due to the isotropic incidence of the electrons was calculated using the data by KANTER. Contrary to the number albedoes, the calculated absorbed dose backscatter coefficients are somewhat dependent on the energy of the incident electrons. This energy dependence is, however, small compared to the overall uncertainty in the determination of b_Z and b_X . For this reason the same values of b_Z and b_X were adopted for both primary radiation qualities. The values adopted are $b_Z=0.74$ and $b_X=0.45$, so that the value of the quantity given in eq. (39) is 1.8.

Comments on the angular distribution of electrons at interfaces. The above choice of backscatter coefficients did imply the two assumptions (a) and (b) which are further discussed in the following.

(a): The electrons escaping from the Pb-foil are generated in a foil thick compared to the range of the electrons. Thus, there are probably relatively more electrons escaping in the forward direction than from a plane isotropic electron source: from a certain depth in the Pb-foil only electrons emitted in the forward direction can reach the interface.

(b): When the electrons from a point isotropic source are incident on a backing material, an anisotropy of the backscattered electrons is found (SELIGER 1952, KANTER 1957). From a high Z material electrons are scattered preferentially perpendicularly backwards, whereas from a low Z material such as lucite they escape preferentially at small angles to the surface (SELIGER). Thus, when electrons are multiply scattered between lead and mylar, eq. (36), there are probably differences in the relative angular distributions of the incident and backscattered electrons, contrary to the assumption made above. In the case when the electrons are multiply scattered from lead to lead, eq. (35), the assumption that there is no change in the angular distribution of the backscattered electrons is, however, better. In consequence, two different values for the absorbed dose backscatter coefficient, b_Z , of lead actually appear in eq. (39).

DUTREIX & BERNARD (1965) estimated values of b_Z and b_X for the secondary electrons generated by ^{60}Co gamma radiation and 20 MV roentgen rays. They measured experimentally D_{ZZ} (D_{XX}), D_Z^F (D_X^F), D_Z^B (D_X^B) and estimated b_Z (b_X) from an equation equivalent to eq. (35). These values of b_Z and b_X were tested at interfaces between slabs of media of different Z and X: the absorbed

dose at the interface was both measured and calculated from equations equivalent to eq. (36). They obtained reasonably good agreement between the measured and calculated absorbed dose. Thus it seems reasonable to use the same value of the absorbed dose backscatter coefficient in both of eqs (35) and (36). With ^{60}Co gamma radiation DUTREIX & BERNARD obtained $b_{\text{Pb}}=0.58$, $b_{\text{mylar}}=0.12$, and with 20 MV roentgen rays $b_{\text{Pb}}=0.49$, $b_{\text{mylar}}=0.08$. The absorbed dose backscatter coefficients calculated for the secondary electrons of 100 to 200 kV roentgen radiation are, as could be expected, higher than those obtained with the secondary electrons of ^{60}Co gamma radiation and 20 MV roentgen radiation. Remarkable is, however, that when the latter values are applied to eq. (39), this equation gives results, 2.0 (^{60}Co) and 1.7 (20 MV), which are close to the 1.8 obtained with the values of $b_{\text{Pb}}=0.74$ and $b_{\text{mylar}}=0.45$ calculated for the radiation qualities of interest (100 kV and 200 kV). Although the values $b_z=0.74$ and $b_x=0.45$ adopted above are uncertain, it seems to be realistic to assume that the quantity given by eq. (39) is a number close to 2.

*Introduction of electron multiple scattering into the simplified theory.
Application to the plane Pb-mylar interface*

The calculated absorbed dose (simplified theory, Fig. 14) from the electrons generated in Pb was at all depths divided with the factor 1.8 yielded by eq. (39) above (Fig. 15).

The results given in Fig. 15 can also be obtained by the simplified theory if the ratio between the assumed straight line ranges of the electrons in mylar and lead, assumption (3), is taken to be a factor of 1.8 greater than originally assumed. This is the same as assuming that the ratio between the straight line ranges is a factor of 1.8 greater than the ratio between the full rectified ranges (c.s.d.a.). When compared to the calculations on electron energy dissipation in different media by SPENCER (1959) this seems to be a reasonable assumption. SPENCER calculated the energy dissipation as a function of the distance from a point isotropic source of monoenergetic electrons in an infinite homogeneous medium. The distance from the electron source is given as a fraction of the full rectified range (c.s.d.a.). In this way the energy dissipation distribution varies only slowly with the initial energy of the electrons. For 100 keV electrons the energy dissipation becomes zero at a distance of 0.96 and 0.63 times the full rectified ranges in a low Z material such as polystyrene, $(\text{C}_8\text{H}_8)_n$, and lead, respectively. Thus, in terms of the full rectified ranges (path lengths) the maximum penetration depth of the electrons is a factor of 1.5 greater in polystyrene than in lead. Due to the neglect of path length straggling the energy dissipation distributions by SPENCER are, however, less accurate at large distances from the

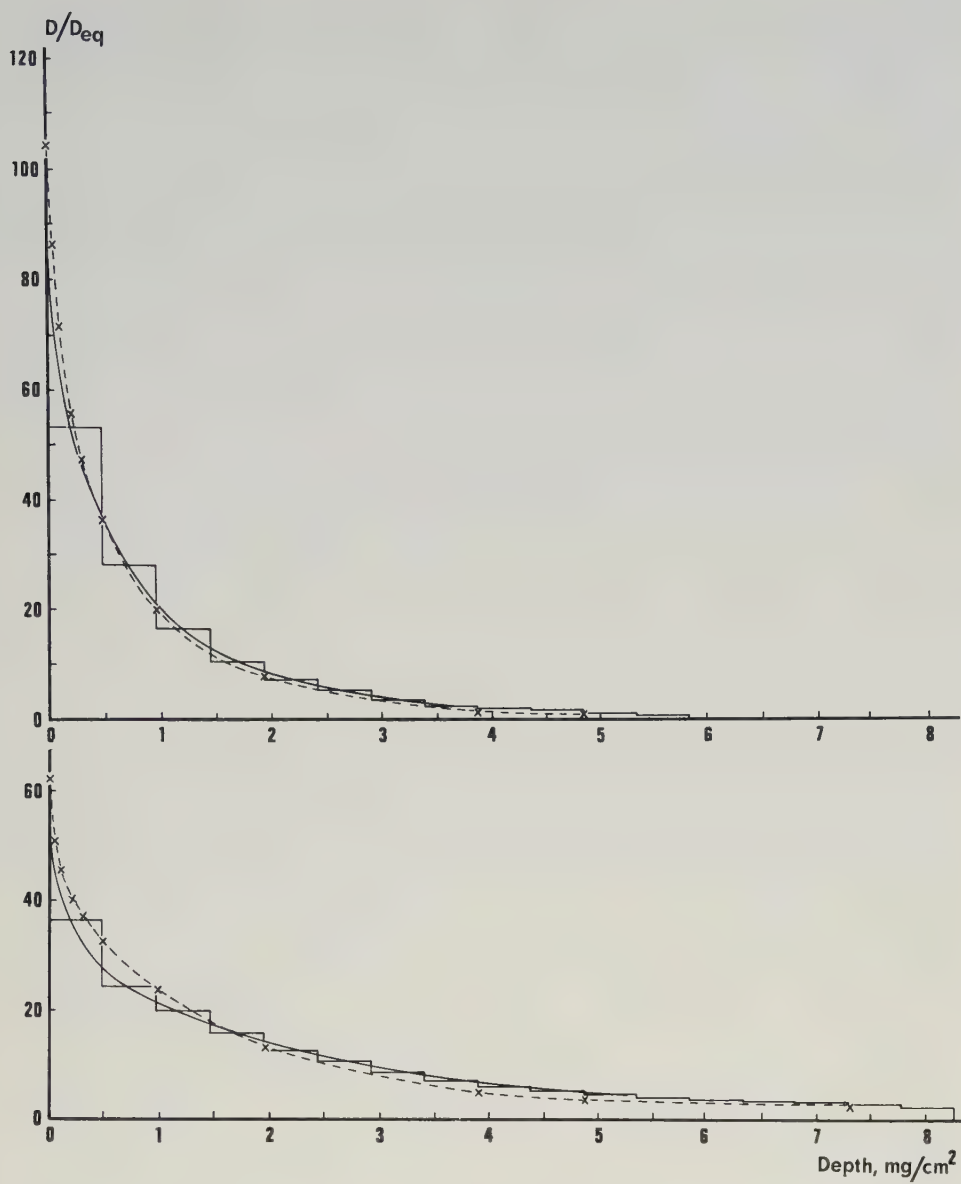


Fig. 15. a) and b) Calculated ($\times$ — — — $\times$, modified calculation) and experimentally determined (—) relative dose distributions, D/D_{eq} , in mylar adjacent to a plane metal foil of Pb, irradiated with a roentgen beam of 100 kV (a, top) and 200 kV (b, bottom). The solid curves are fitted to the histograms obtained experimentally.

electron source. From his curves, extrapolated ranges of the electrons were estimated, the values being 0.91 and 0.44 times the full rectified range in polystyrene and lead, respectively. In terms of the full rectified ranges, the extrapolated range in polystyrene is a factor of 2.1 greater than that in lead.

The agreement between the calculated curves in Fig. 15 and the experimental results is surprisingly good. The experimental curves show a deeper penetration into mylar than the calculated curves. This is in agreement with a more recent evaluation of the influence function by CHARLTON (1970). He uses a more realistic approach to the electron straight line range based on the above mentioned calculations by SPENCER (1959). This new approach to the electron straight line range only concerns the assumption (4) mentioned above and is not involved in assumption (3) about the ratio between the straight line ranges of the electrons in the two different media.

The influence function given by HOWARTH (1965) implies that the electrons do not penetrate depths > 0.7 times the full rectified range, i.e. at a distance > 0.7 times the full rectified range from the interface, the dose contribution from electrons generated in lead is regarded as zero. This evidently underestimates the real penetration depth.

Deviation between the calculated (simplified theory) and experimentally determined absorbed doses as a function of the atomic number of the adjacent material

The relative absorbed doses in mylar close to the metal foils of Sn and Cu were calculated in the same way as for Pb according to the simplified theory. In Fig. 16 the quotient between the calculated absorbed dose and the 'measured' absorbed dose close to a metal foil is given as a function of the atomic number, with the quality of the primary radiation as a parameter. It is here of interest to compare the quotients given in Fig. 16 with the quantity given in eq. (39). Absorbed dose backscatter coefficients for Al, Cu and Sn were estimated in the same way as for Pb and mylar: $b_{\text{Al}}=0.53$, $b_{\text{Cu}}=0.63$, $b_{\text{Sn}}=0.69$. Eq. (39) then yields a value of 1.5, 1.3 and 1.1 with Sn, Cu and Al, respectively. The quantity in eq. (39) gives the quotient between the calculated (simplified theory) and real absorbed dose from only the electrons generated in the metal foil, while Fig. 16 gives the quotient between the calculated and the 'measured' total absorbed doses. With Sn and Cu, as well as with Pb, the dominant contribution to the total absorbed dose is from electrons generated in the metal foil and there is, especially with 200 kV radiation, relatively good agreement between the predicted, eq. (39), and the experimentally estimated overestimates in the cal-

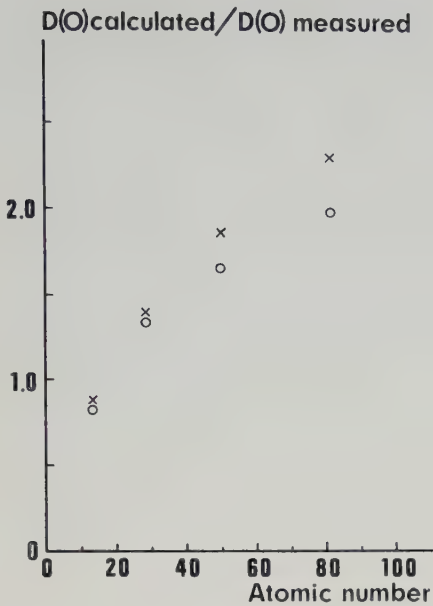


Fig. 16. The quotient between the calculated and the experimentally determined absorbed doses in mylar adjacent to metal foils of Al, Cu, Sn and Pb, represented as a function of the atomic number with the quality of the primary radiation, 100 kV (X) and 200 kV (O), as a parameter.

culated absorbed dose. With Al, a considerable fraction of the total absorbed dose is due to electrons generated in mylar, especially with 200 kV radiation. Furthermore, eq. (39) is valid provided that the electrons are isotropically emitted or strongly scattered within the metal foil. The photoelectrons are, however, emitted with some preference for the forward direction and the scattering in Al is not strong enough to smooth this out. The measurements by WINGATE et coll. (1962) show that the relative absorbed dose in soft tissue close to a plane interface of bone is somewhat dependent on the beam direction. The relative absorbed dose, D/D_{eq} , in soft tissue is higher at a bone-soft tissue interface than at a soft tissue-bone interface. The dependence on the beam direction did not vary much over primary radiation qualities from 30 kV to 210 kV. Since in this investigation the measurements have been performed at an Al-mylar interface, it seems reasonable that the 'measured' absorbed dose exceeds the calculated absorbed dose (Fig. 16). Though the precision in the measurements with Al is not good enough to prove this relation, it is noteworthy that the results obtained with the two different radiation qualities show up the same effect.

From the above discussion it seems quite convincing that the main behaviour of the quotients given in Fig. 16 is an effect of the neglect of electron scattering in the simplified theory. The quotients given in Fig. 16 can be taken as a rough indication of the limitations of this theory, with regard to the atomic number

of the adjacent material, at a plane interface. The difference between the quotients at 100 kV and at 200 kV is discussed in the next section.

Dead layer of LiF-grains

The comparison between the theoretical and experimental results seems to indicate that there is at least no great difference between the weighted mean efficiency of the surface layers, $\overline{\eta}_s$, and the mean efficiency, $\overline{\eta}$, over all depths of the detectors. One factor which could contribute to a relatively low weighted mean efficiency of the surface layers is a possible dead layer at the surface of the LiF-grains. In fact, the measurements of ZANELLI (1968) seem to indicate the presence of such a layer. ZANELLI investigated the TL-emission as a function of the mean particle diameter. The TL-emission is essentially independent of the mean particle diameter down to values of about 10 to 20 μm , where the TL-emission starts to decrease rapidly with decreasing diameter, reaching a value of 50 per cent when the diameter is about 3 μm . Assuming the LiF-grains to be spheres, a dead layer of 0.3 μm thickness at the surface is enough to reduce the active volume to 50 per cent of the total volume when the sphere diameter is 3 μm .

There may thus possibly be a dead layer of thickness up to 0.3 μm at the surface of the LiF-teflon discs. This means that the measured depth doses actually start at a depth of $\approx 0.07 \text{ mg/cm}^2$ from the interface. The quotient between the calculated (simplified theory) absorbed dose in mylar at a distance of 0.07 mg/cm^2 from the Pb-mylar interface and the 'measured' absorbed dose at zero depth (Fig. 14) is 1.7 and 1.6 with 100 kV and 200 kV radiation, respectively. Thus, by assuming the presence of a dead layer $\leq 0.3 \mu\text{m}$, the quotient between the calculated and 'measured' absorbed dose close to the interface is actually, with both radiation qualities, closer to the value of 1.8 estimated above than to the values of 2.3 and 2.0 in Fig. 14. This is also demonstrated in Fig. 15.

In Fig. 16 the quotient between the calculated absorbed dose and the experimentally determined absorbed dose is somewhat higher at 100 kV than at 200 kV independent of the atomic number of the metal foil. A dead layer at the surface of the detectors should cause this effect as the dose gradients are steeper at 100 kV than at 200 kV. There are, however, other possible explanations for the observed effect. The forward direction of the photoelectrons is more marked at 200 kV than at 100 kV. As, however, the Rutherford scattering of electrons is stronger in the higher Z materials the discrepancy between the quotients at 100 kV and at 200 kV should rather decrease than increase with the atomic number. The correction, eq. (39), for the effect of multiple scattering

of the electrons on the calculated absorbed dose at the plane interface may also, in opposition to the assumptions made above, be somewhat dependent on the quality of the primary radiation. An electrostatic charging of the insulators (LiF, mylar) during the irradiation with the photoelectrons would evidently influence the results (KASTNER et coll. 1967, HARRAH 1970). The effect of electrostatic charging increases with increasing fluence of the incident electrons and is not present in a conducting material as soft tissue. It is a general problem that arises in electron dosimetry using insulators as phantom material (ROSENSTEIN 1971). KASTNER et coll. noticed that the thermoluminescent response to tritium β -rays (mean energy 5.5 keV) dropped rapidly with the time of irradiation. This effect was explained as due to a charging of the LiF-crystal, so that after sufficiently high doses many of the incident low energy tritium β -particles were repelled by the crystal. No such effect was, however, seen with β -rays of somewhat higher energies as those of ^{63}Ni with a mean energy of 18 keV. As the mean energy of the photoelectrons emitted from the metal foils is higher than that of the tritium β -particles a possible charging effect is supposed to be small here. The presence of a metal layer in contact with the insulators also reduces the electrostatic charging (HOLLIDAY & STERNGLOSS 1957). This problem deserves, however, further investigation.

Among possible explanations of the discrepancy between the quotients at 100 kV and 200 kV (Fig. 16) the presence of a dead layer in LiF about $0.3\ \mu\text{m}$ thick seems to be the most plausible.

CONCLUSIONS

The equilibrium fluence of electrons in a high Z material is to a great extent caused by multiply scattered electrons, i.e. by electrons which contribute to the fluence by passing several times through an extended plane surface. At a plane interface between a high Z and a low Z material the scattering conditions are considerably changed. Electrons generated in the high Z material which pass the interface for the first time are not as effectively scattered back as from the high Z material, resulting in a reduced electron fluence at the interface. In the simplified theories discussed above, it seems possible for plane interfaces to take the effect of electron scattering into account by modifying the assumption about the ratio between the presumed straight line ranges of the electrons in the two media. It is, however, not realistic to adopt the same value of the straight line range ratio independently of the interface geometry. Within spheres, cylinders and other cavities, the electrons can be scattered between the cavity walls and the scattering conditions approach the scattering conditions in the homogeneous high Z material, the approximation being better the smaller the cavity. For very small cavities, i.e. approximate Bragg-Gray cavities, the original theory yields approximately the correct value for the mean absorbed dose in the cavity. Therefore, in cavity ionization theories which include finite size cavities, it seems to be relevant to take electron scattering into account. In a more recent cavity ionization theory for finite size cavities by BURLIN (1966) electron scattering is also neglected, which is believed to limit the accuracy of this theory, the degree of limitation depending on the dimension and geometry of the cavity as well as on the atomic number of the cavity walls.

The results of the depth dose measurements within the transition region seem to be reliable. (Recently measurements of depth doses within the transition region have been performed by ENNOW using thermally stimulated exoelectron emitting (TSEE) LiF as a detector (ENNOW 1972). The choice of radiation quality and irradiation geometry was copied from my experiments to make a comparison of our results possible. Our results, obtained with fundamentally different methods of measurement, are essentially in good agreement. Though ENNOW takes this agreement as promising as regards the application of the TSEE method in dosimetry measurements it gives as well support to the reliability of my measurements.) Dose enhancement factors, D/D_{eq} , of as large as 50 directs the

interest to the radiologic applications of low energy roentgen rays and high Z materials. Behind a high Z contrast medium, the roentgen rays are often heavily attenuated but relatively high absorbed doses may be obtained at the focus side of the contrast medium. The biologic significance of these enhanced doses cannot be analyzed here. The intention of the present investigation was rather to direct the attention towards the magnitude of dose enhancements which may be locally received by the patients in preferentially roentgen diagnostic examinations. The dose enhancement factors obtained with the 100 kV radiation, both at points close to the interface and when averaged over a 0.486 mg/cm^2 thick layer of soft tissue close to the interface (Fig. 12), represent high values. The calculated dose enhancement factors close to the interface for monoenergetic photons exhibit a maximum at photon energies between 20 keV and 50 keV, depending on the atomic number of the adjacent material. With all atomic numbers, the calculated maximum dose enhancement factor for monoenergetic photons is only about a factor of 1.5 higher than the calculated dose enhancement factor for the 100 kV radiation as averaged over primary as well as secondary photons. The results obtained with the 100 kV radiation therefore roughly give the maximal dose enhancements that can at plane interfaces occur with spectra of roentgen radiation. When the soft tissues are completely surrounded by the high Z material the dose enhancement can be as much as a factor of 4 higher (Pb) than that at the plane interface.

Frequently, high Z contrast media are not used in a pure state but are mixed with substances of lower Z. It follows that the actual dose enhancement factors are lower than those of the homogeneous high Z material.

APPENDIX

Effects of the different electron scattering properties of mylar and LiF-teflon

LiF and teflon (C_2F_4)_n scatter electrons more effectively than mylar ($\text{C}_{10}\text{H}_8\text{O}_4$)_n. The stronger scattering of electrons by the fluorine atoms in the LiF-teflon detector than by the carbon atoms in a polystyrene phantom irradiated by 0.66 MeV γ -rays has been clearly verified by SAMUELSSON & CARLSSON. This observation motivated the following analysis.

Let E_0 be the sum of the kinetic energies of the electrons generated in a metal foil of atomic number Z which traverse the interface between the metal foil and the detector for the first time. The energy, $[\bar{\varepsilon}_0]_{Z,L}$, absorbed in the LiF-teflon detector (zero interposed mylar films) can be written:

$$[\bar{\varepsilon}_0]_{Z,L} = E_0 - E_0 \cdot b_L + E_0 \cdot b_L \cdot b_Z - E_0 \cdot b_L \cdot b_Z \cdot b_L' + \\ + E_0 \cdot b_L \cdot b_Z \cdot b_L' \cdot b_Z' - E_0 \cdot b_L \cdot b_Z \cdot b_L' \cdot b_Z' \cdot b_L'' + \dots \quad (40)$$

$b_L, b_L', b_L'', \dots$ and $b_Z, b_Z', b_Z'', \dots$ are the energy albedoes of LiF-teflon and the metal foil, respectively, valid for the actual energy and angular distribution of the incident electrons.

With low energy electrons, < 200 keV, both the number albedo and the fractional mean energy loss of the backscattered electrons are approximately independent of the electron energy (KANTER 1957). Provided that the influence of a change in the angular distribution of the incident electrons is negligible, it is a reasonable approximation to write $b_L \simeq b_L' \simeq b_L'' \simeq \dots$, and $b_Z \simeq b_Z' \simeq b_Z'' \simeq \dots$. $[\bar{\varepsilon}_0]_{Z,L}$ may then be written:

$$[\bar{\varepsilon}_0]_{Z,L} = E_0 \cdot \frac{(1-b_L)}{(1-b_L \cdot b_Z)} \quad (41)$$

Consider the absorbed energy, $[\bar{\varepsilon}_0]_{Z,m}$, in a thick layer of mylar at the same location as the LiF-teflon detector.

Then

$$[\bar{\varepsilon}_0]_{Z,m} = E_0 \cdot \frac{(1-b_m)}{(1-b_m \cdot b_Z)} \quad (42)$$

Here b_m is the energy albedo of mylar.

For large numbers, i , of interposed mylar films, the scattering of electrons between the detector and the metal foil becomes negligible. Let E_i be the sum of kinetic energies of the electrons generated in the metal foil traversing the interface between the mylar films and the LiF-teflon detector for the first time. The absorbed energy, $[\bar{\epsilon}_i]_{Z,L}$, in the detector is then obtained from eq. (41) by substituting b_Z with b_m , and E_0 with E_i :

$$[\bar{\epsilon}_i]_{Z,L} = E_i \cdot \frac{(1-b_L)}{(1-b_L \cdot b_m)} \quad (43)$$

The absorbed energy, $[\bar{\epsilon}_i]_{Z,m}$, in a thick layer of mylar at the same location is, from eq. (42) with $b_Z=b_m$, and $E_0=E_i$:

$$[\bar{\epsilon}_i]_{Z,m} = E_i \cdot \frac{1}{(1+b_m)} \quad (44)$$

The mean absorbed dose, $[\bar{D}_{m,i+1}]_Z$, in the mylar film number $i+1$ from electrons generated in the metal foil when the electrons are completely stopped in mylar is given by

$$[\bar{D}_{m,i+1}]_Z = \frac{1}{A \cdot \Delta t} ([\bar{\epsilon}_i]_{Z,m} - [\bar{\epsilon}_{i+1}]_{Z,m}) \quad (45)$$

Values of energy albedoes were derived using data of number albedoes from KANTER (1957) and SELIGER (1952) and of fractional mean energy losses from BISHOP (1967) and KANTER. The number albedoes for an isotropic point electron source were used, thereby assuming that the incident electrons have the same angular distribution as the electrons from a plane isotropic electron source. The mean fractional energy losses given by BISHOP are valid for perpendicularly incident electrons. They were corrected to take account of the decrease in the mean energy loss due to the isotropic incidence of the electrons as estimated from the measurements by KANTER. The calculated values of the energy albedoes are then: $b_{Pb}=0.52$, $b_{Sn}=0.47$, $b_{Cu}=0.39$, $b_{Al}=0.30$, $b_L=0.25$, $b_m=0.22$.

For large numbers of i , the quotient between $[\bar{\epsilon}_i]_{Z,L}$ and $[\bar{\epsilon}_i]_{Z,m}$ is 0.968. Thus $[\bar{\epsilon}_i]_{Z,L} - [\bar{\epsilon}_{i+1}]_{Z,L}$ yields an underestimate of $[\bar{\epsilon}_i]_{Z,m} - [\bar{\epsilon}_{i+1}]_{Z,m}$, the relevant quantity of eq. (45) by about 3 per cent.

With $i=0$, the quotient between $[\bar{\epsilon}_0]_{Z,L}$ and $[\bar{\epsilon}_0]_{Z,m}$ is closer to 1 due to the increased backscattering from the metal foil. For example, with Pb the quotient between $[\bar{\epsilon}_0]_{Z,L}$ and $[\bar{\epsilon}_0]_{Z,m}$ is 0.979. An estimate of the discrepancy between $[\bar{\epsilon}_0]_{Z,L} - [\bar{\epsilon}_1]_{Z,L}$ and $[\bar{\epsilon}_0]_{Z,m} - [\bar{\epsilon}_1]_{Z,m}$ was made by assuming that the quotient between $[\bar{\epsilon}_1]_{Z,L}$ and $[\bar{\epsilon}_1]_{Z,m}$ is given by a mean value of the quotients for $i=0$ and for large numbers of i . It was then found that $[\bar{\epsilon}_0]_{Z,L} - [\bar{\epsilon}_1]_{Z,L}$ yields an underestimate of $[\bar{\epsilon}_0]_{Z,m} - [\bar{\epsilon}_1]_{Z,m}$ of < 1 per cent when $Z=82$ (Pb), of 1 to 2 per cent when $Z=50, 29$ (Sn, Cu), and of 3 per cent when $Z=13$ (Al).

SUMMARY

Depth dose contributions from photoelectrons and characteristic roentgen rays in low Z materials (mylar, teflon) close to foils of Al, Cu, Sn or Pb have been measured by means of thermoluminescent LiF embedded in 0.13 mm thick teflon discs. Dose contributions from the K-radiation of Cu and Sn as well as the L-radiation of Pb are clearly verified. Dose enhancements, D/D_{eq} , within the transition region (electronic nonequilibrium) of as much as 50 directs interest towards the radiologic applications of low energy roentgen rays and high Z materials in, for example, roentgen diagnostic examinations. Ba ($Z=56$) and I ($Z=53$) are widely used as contrast media and in dental diagnostic procedures the roentgen rays pass through soft tissues in contact with very high Z materials such as Hg ($Z=80$) and Au ($Z=79$). The results obtained with the 100 kV roentgen radiation can be taken as a guide about maximum possible dose enhancements with spectra of roentgen radiation.

As the detectors are thin compared to the mean free path of the photons but infinitely thick compared to the range of the secondary electrons, different methods of measurement were used in determining the depth doses within the region of electronic equilibrium and within the transition region, respectively. Within the region of electronic equilibrium the detectors were calibrated and used as dosimeters. Within the transition region, the dose distribution was resolved by successively increasing the number of thin mylar films, 0.486 mg/cm² thick, between the metal foil and the detector.

A thorough analysis of the LiF-teflon detector is performed with special regard to the efficiency (=detector signal per unit absorbed energy), which is a function of the depth in the detector as well as varying from one individual detector to another. A special problem concerns the relation between the weighted mean efficiency of the surface layers in which the photoelectrons from the metal foil are absorbed and the mean efficiency averaged over all depths of the detector. The influence of the differences in the electron scattering properties of mylar and teflon upon the interpretation of the experimental results is discussed together with other effects caused by the mylar-teflon interface.

A comparison is made between measured and calculated dose distributions within the transition region. The calculations were performed using a simplified theory originally developed by SPIERS (1949) and refined first by CHARLTON &

CORMACK (1962) and then by HOWARTH (1965). This theory was developed to calculate dose distributions at bone-soft tissue interfaces, i.e. at interfaces between media differing not too much in atomic composition. An extension of the theory to interfaces between soft tissue and a high Z material was performed by ASPIN & JOHNS (1963). CHARLTON (1970) in a later work also provided a method to extend the original theory to interfaces between two arbitrary media. The calculations for the high Z interfaces were performed according to HOWARTH in combination with the developments outlined by ASPIN & JOHNS and CHARLTON. Thus, close to a plane interface this theory predicts the absorbed dose in the low Z material to be equal to the sum of half of the Bragg-Gray-Laurence dose in the low Z material under electronic equilibrium conditions in the high Z material and half of the absorbed dose under electronic equilibrium conditions in the low Z material. There is good agreement between the measured and calculated dose distributions at the Al-interfaces but close to Pb the calculated absorbed dose is a factor of 2 higher than that determined experimentally. The disagreement is shown to be due to the neglect of electron scattering in the simplified theory. A quantitative estimate of the effect of electron multiple scattering upon the absorbed dose at a plane interface between different media is made using an equation given by DUTREIX & BERNARD (1965) and the available data about the backscattering of low energy (< 200 keV) electrons. A modification of the simplified theory for plane interfaces is discussed. It is pointed out that because of changes in the electron scattering conditions the same modification cannot be used for other interface geometries, for example, spherical or cylindrical.

The influence of a possible non-thermoluminescent layer, i.e. a dead layer, at the surface of the LiF-grains upon the interpretation of the experimental results is discussed.

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REFERENCES

- ALM CARLSSON G.: A criticism of existing tabulations of mass energy transfer- and mass energy absorption coefficients. *Hlth Phys.* 20 (1971), 653.
- ASPIN N. and JOHNS H. E.: The absorbed dose in cylindrical cavities within irradiated bone. *Brit. J. Radiol.* 36 (1963), 350.
- BERGER M. J.: Monte Carlo calculation of the penetration and diffusion of fast charged particles. *In: Methods in computational physics.* Vol. 1, p. 135. Edited by B. Alder, S. Fernbach and M. Rotenberg. Academic Press, New York and London 1963.
- and RASO D. J.: Monte Carlo calculations of gamma-ray backscattering. *Radiat. Res.* 12 (1960), 20.
- and SELTZER S. M.: Tables of energy losses and ranges of electrons and positrons. SP-3012, National Aeronautics and Space Administration, Washington 1964.
- — Additional stopping power and range tables for protons, mesons, and electrons. SP-3036, National Aeronautics and Space Administration, Washington 1966.
- BERGER R. T.: The X- or gamma-ray energy absorption or transfer coefficient: tabulations and discussion. *Radiat. Res.* 15 (1961), 1.
- BISHOP H. E.: Some electron backscattering measurements for solid targets. *In: Proceedings of the 4th international conference on X-ray optics and microanalysis*, p. 153. Hermann, Paris 1966.
- Electron scattering in thick targets. *Brit. J. appl. Phys.* 18 (1967), 703.
- BJÄRNGÅRD B. and HETTINGER G.: Spectra of scattered radiation behind slabs of water irradiated by X-rays. *Ark. Fysik* 20 (1961), 517.
- McCALL R. C. and BERSTEIN I. A.: Lithium fluoride-teflon thermoluminescence dosimeters. *In: Proceedings of international conference on luminescence dosimetry*, p. 308. Report CONF-65 06 37. United States Atomic Energy Commission, Springfield 1967.
- BOTHE W.: Zur Rückdiffusion schneller Elektronen. *Z. Naturforsch.* 4 a (1949), 542.
- BRAND J. O.: Über die Energieverteilung rückdiffundierter Kathodenstrahlen. *Ann. Physik* 5. Folge, Bd. 26 (1936), 609.
- BRUCE W. R. and JOHNS H. E.: The spectra of X-rays scattered in low atomic number materials. *Brit. J. Radiol.* (1960) Suppl. No. 9.
- BURLIN T. E.: A general theory of cavity ionization. *Brit. J. Radiol.* 39 (1966), 727.
- Cavity-chamber theory. *In: Radiation Dosimetry.* Vol. 1, p. 331. Edited by F. H. Attix and W. C. Roesch. Academic Press, New York and London 1968.
- CAMERON J. R., DE WERD L., WAGNER J., WILSON C., DOPPKE K. and ZIMMERMAN D.: Non-linearity of thermoluminescence as a function of dose for LiF (TLD-100). *In: Proceedings of the symposium on solid state and chemical radiation dosimetry in medicine and biology*, p. 77. International Atomic Energy Agency, Vienna 1967.
- CARLSSON C. A.: Determination of integral absorbed dose from exposure measurements. *Acta radiol. Ther. Phys. Biol.* 1 (1963), 433.
- and ALM CARLSSON G.: Induced LET-dependence in thermoluminescent LiF and its application as LET-meter. *In: Proceedings of the second international conference on luminescence*

- dosimetry, p. 353. Report CONF-68 09 20. United States Atomic Energy Commission, Springfield 1968.
- — Proton dosimetry: measurement of depth doses from 185-MeV protons by means of thermoluminescent LiF. *Radiat. Res.* 42 (1970), 207.
- MÄRTENSSON B. K. A. and ALM CARLSSON G.: High precision dosimetry using thermoluminescent LiF. *In: Proceedings of the second international conference on luminescence dosimetry*, p. 936. Report CONF-68 09 20. United States Atomic Energy Commission, Springfield 1968.
- CHARLTON D. E.: Energy dissipation near an interface: a more realistic approach to electron range and stopping power. *Radiat. Res.* 44 (1970), 575.
- and CORMACK D. V.: Energy dissipation in finite cavities. *Radiat. Res.* 17 (1962), 34.
- DOPPKE K. P. and CAMERON J. R.: Radiation damage in LiF (TLD-100). *Phys. in Med. Biol.* 11 (1966), 624.
- — Desensitization of LiF (TLD-100) due to radiation damage. Report COO-1105-119. United States Atomic Energy Commission, Springfield 1966.
- DUTREIX J. et BERNARD M.: Étude du flux des électrons secondaires et de leur rétrodiffusion. *Biophysik* 2 (1965), 179.
- — Dosimetry at interfaces for high energy X- and gamma rays. *Brit. J. Radiol.* 39 (1966), 205.
- DUTREIX A. and TUBIANA M.: Electronic equilibrium and transition stages. *Phys. in Med. Biol.* 10 (1965), 177.
- ENNOW K.: Some TSEE measurements of dose gradients at interfaces. *In: Proceedings of the symposium on dosimetry techniques applied to agriculture, industry, biology and medicine.* International Atomic Energy Agency, Vienna 17—21 April 1972. In press.
- EPP E. R., WOODARD H. Q. and WEISS H.: Energy absorption by the bone marrow of the mouse receiving wholebody irradiation with 250- kV X-rays or cobalt-60 gamma rays. *Radiat. Res.* 11 (1959), 184.
- FELDMAN A. and MORKOVIN D.: Cell dosimetry. *Radiology* 74 (1960), 112.
- FINK R. W., JOPSON R. C., MARK H. and SWIFT C. D.: Atomic fluorescence yields. *Rev. mod. Phys.* 38 (1966), 513.
- FOWLER J. F.: Absorbed dose near bone; a conductivity method of measurement. *Brit. J. Radiol.* 30 (1957), 361.
- GORBICS S. G. and ATTIX F. H.: LiF and CaF_2 : Mn thermoluminescent dosimeters in tandem. *Int. J. appl. Radiat.* 19 (1968), 81.
- GRAY L. H.: Physical investigation of the contribution of the photo-electrons from sulphur to X-ray ionisation. *Brit. J. Radiol.* 13 (1940), 25.
- HARDER D. und FERBERT H.: Rückdiffusion schneller Elektronen im Energiebereich 8 bis 22 MeV. *Phys. Lett.* 9 (1964), 233.
- HARRAH L. A.: Stored charge effects on electron dose-depth profiles in insulators. *Appl. phys. Lett.* 17 (1970), 421.
- HENDEE W. R. and KENNEDY K.: Thermoluminescent measurement of cellular radiation dose. *Amer. J. Roentgenol.* 100 (1967), 886.
- HETTINGER G.: Angular and spectral distributions of backscatter radiation from slabs of water, brass, and lead irradiated by photons between 50 and 250 keV. *Acta radiol.* 54 (1960), 1.
- and STARFELT N.: Bremsstrahlung spectra from roentgen tubes. *Acta radiol.* 50 (1958), 381.
- — Energy and angular distribution of scattered radiation in a water tank irradiated by X-rays. *Ark. Fysik* 14 (1959), 497.

- HINE G. J.: Scattering of secondary electrons produced by γ -rays in materials of various atomic numbers. *Phys. Rev.* 82 (1951), 755.
- HOLLIDAY J. E. and STERNGLASS E. J.: Backscattering of 5—20 keV electrons from insulators and metals. *J. appl. Phys.* 28 (1957), 1189.
- HOOD S. L. and NORRIS G.: Dosimetry of human cell cultures irradiated at the interface in plastic and in glass dishes. *Radiat. Res.* 14 (1961), 705.
- HOWARTH J. L.: Calculation of the absorbed dose in soft tissue cavities in bone irradiated by X-rays. *Radiat. Res.* 24 (1965), 158.
- HUBBELL J. H.: Photon cross sections, attenuation coefficients, and energy absorption coefficients from 10 keV to 100 GeV. Report NSRDS-NBS 29. National Bureau of Standards, Washington 1969.
- INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS (ICRU): Physical aspects of irradiation Report 10 b, Washington 1964.
- Linear energy transfer. Report 16, Washington 1970.
- KANTER H.: Zur Rückstreuung von Elektronen im Energiebereich von 10 bis 100 keV. *Ann. Physik* 6. Folge, Bd. 20 (1957), 144.
- KASTNER J., HUKKOO R., OLTMAN B. G. and DAYAL Y.: Thermoluminescent internal beta-ray dosimetry. *Radiat. Res.* 32 (1967), 625.
- KRAMER J.: Exoelektronen-Dosimeter für Röntgen- und Gammastrahlen. *Z. angew. Phys.* 20 (1966), 411.
- KRÜGER E., MATSCHKE S. und FRANK M.: Energieabsorptionsmessungen von Co^{60} an der Grenzschicht Muskel-Knochen mit LiF -Einkristallen. *Strahlentherapie* 129 (1966), 559.
- LENTSCH J. W. and FINSTON R. A.: Increased X-ray dose adjacent to plane bone interfaces as measured in polyethylene. *Phys. in Med. Biol.* 12 (1967), 543.
- MARRONE M. J. and ATTIX F. H.: Damage effects in CaF_2 : Mn and LiF thermoluminescent dosimeters. *Hlth Phys.* 10 (1964), 431.
- MÄRTENSSON B. K. A.: Thermoluminescence of LiF : a statistical analysis of the influence of pre-annealing on the precision of measurement. *Phys. in Med. Biol.* 14 (1969), 119.
- MCGINNIES R. T.: Energy spectrum resulting from electron slowing down. NBS Circular 597. National Bureau of Standards, Washington 1959.
- MORKOVIN D. and FELDMAN A.: Dosimetry in living cells irradiated on glass: a correction. *Brit. J. Radiol.* 32 (1959), 282.
- MUNSON R. J.: A note on the paper by F. W. Spiers (*Brit. J. Radiol.* 22 (1949), 521) entitled 'The influence of energy absorption and electron range on dosage in irradiated bone'. *Brit. J. Radiol.* 23 (1950), 505.
- NATIONAL COMMITTEE ON RADIATION PROTECTION AND MEASUREMENTS (NCRP): Stopping powers for use with cavity chambers. NBS Handbook 79, National Bureau of Standards, Washington 1961.
- NAYLOR G. P.: Thermoluminescence phosphors: variation of quality response with dose. *Phys. in Med. Biol.* 10 (1965), 564.
- PATERSON E.: A comparison of the action of X and gamma radiation on fibroblasts. *Brit. J. Radiol.* 15 (1942), 302.
- ROBINSON B. L. and FINK R. W.: Recent experimental results on orbital electron capture. *Rev. mod. Phys.* 32 (1960), 117.
- ROSENSTEIN M.: Electron depth-dose distribution measurements in polystyrene. Thesis. Faculty of the Graduate School of the University of Maryland, 1971.
- SAMUELSSON C. and CARLSSON C. A.: Personal communication.

- SCHULZ R. J.: Interface dosimetry with LiF-teflon microdosimeters. *In: Proceedings of the symposium on microdosimetry*, p. 643, Eur 3747 d-f-e. European Atomic Energy Community, Brussels 1968.
- SELIGER H. H.: The backscattering of positrons and electrons. *Phys. Rev.* 88 (1952), 408.
- SINCLAIR W. K.: The relative biological effectiveness of 22-Mevp X-rays, cobalt-60 gamma rays, and 200-Kvcp X-rays. V. Absorbed dose to the bone marrow in the rat and the mouse. *Radiat. Res.* 16 (1962), 369.
- SPENCER L. V.: Energy dissipation by fast electrons. NBS Monograph 1, National Bureau of Standards, Washington 1959.
- Remarks on the theory of energy deposition in cavities. *Acta radiol. Ther. Phys. Biol.* 10 (1971), 1.
- and FANO U.: Energy spectrum resulting from electron slowing down. *Phys. Rev.* 93 (1954), 1172.
- and ATTIX F. H.: A theory of cavity ionization. *Radiat. Res.* 3 (1955), 239.
- SPIERS F. W.: The influence of energy absorption and electron range on dosage in irradiated bone. *Brit. J. Radiol.* 22 (1949), 521.
- Dosage in irradiated soft tissue and bone. *Brit. J. Radiol.* 24 (1951), 365.
- Transition-zone dosimetry. *In: Radiation dosimetry*. Vol. 3, p. 809. Edited by F. H. Attix and E. Tochilin. Academic Press, New York and London 1969.
- STENSTROM K. W. and MARVIN J. F.: Ionization measurements with bone chambers and their application to radiation therapy. *Amer. J. Roentgenol.* 56 (1946), 759.
- STERNGLASS E. J.: Backscattering of kilovolt electrons from solids. *Phys. Rev.* 95 (1954), 345.
- STORM E. and ISRAEL H. I.: Photon cross sections from 1 keV to 100 MeV for elements $Z=1$ to $Z=100$. *Nuclear Data Tables A* 7, 565. Academic Press, New York and London 1970.
- SUNTHARALINGAM N. and CAMERON J. R.: Thermoluminescent response of Lithium Fluoride to radiations with different LET. *Phys. in Med. Biol.* 14 (1969), 397.
- TOCHILIN E., GOLDSTEIN N. and LYMAN J. T.: The quality and LET dependence of three thermoluminescent dosimeters and their potential use as secondary standards. *In: Proceedings of the second international conference on luminescence dosimetry*, p. 424. Report CONF-68 09 20. United States Atomic Energy Commission, Springfield 1968.
- WAPSTRA A. H., NIJGH G. J. and VAN LIESHOUT R.: *Nuclear spectroscopy tables*. North-Holland Publishing Company, Amsterdam 1959.
- WINGATE C. L., GROSS W. and FAILLA G.: Experimental determination of absorbed dose from X-rays near the interface of soft tissue and other material. *Radiology* 79 (1962), 984.
- WOODARD H. Q. and SPIERS F. W.: The effect of X-rays of different qualities on the alkaline phosphatase of living mouse bone. *Brit. J. Radiol.* 26 (1953), 38.
- WRIGHT K. A. and TRUMP J. G.: Back-scattering of megavolt electrons from thick targets. *J. appl. Phys.* 33 (1962), 687.
- ZANELLI G. D.: Thermoluminescence methods applied to dosimetry in trabecular bone. *In: Proceedings of the symposium on microdosimetry*, p. 527. Eur 3747 d-f-e. European Atomic Energy Community, Brussels 1968.

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